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A Novel Approach to Teaching Power Systems Analysis and Design Using Software Development

Paulo Radatz
Dr. Robert J Kerestes, University of Pittsburgh

Robert Kerestes, Ph.D., is an associate professor of electrical and computer engineering at the University of Pittsburgh's Swanson School of Engineering. Robert was born in Pittsburgh, Pennsylvania. He got his B.S. (2010), his M.S (2012), and his Ph.D. (2014)

A Novel Approach to Teaching Power Systems Analysis and Design Using Software Development

Abstract

The study of electric power systems is extremely vital and relevant due to the ongoing efforts to modernize the grid. The authors are trying to shift from carbon-based energy sources to renewable energy sources. This requires developing the workforce of the future which can handle these contemporary challenges. Two of the most useful tools when it comes to the analysis of electric power systems are power flow simulation and fault studies. There are simulators that are provided to universities for educational purposes so that students can learn how to run power flow simulations and use the results for analysis and design. The problem that the authors have observed is that students need a better intuition on how to interpret the results. This leads to students accepting erroneous results simply because the simulation produced them.

In this paper, the authors propose a methodology for teaching power systems analysis that teaches students how to run power flow simulations using a commercial tool and gives them a deep intuition of what the simulator is doing. The authors propose that students learn how to truly learn to use a simulator by developing one from scratch. This simulator is developed over the course of a semester by coupling the active learning techniques of the flipped classroom model and project-based learning. In the course, students watch videos prior to class to learn about modeling and implementation techniques. In the class, students work with instructors and teaching assistants to build a simulator in a modular approach. Students then validate the results of the simulator that they are developing with a commercial simulator.

Using this teaching methodology, students learn the first-principles physics equations for steady-state power systems and the techniques to implement them. As a bonus, the authors can teach students about the software development process giving them an added skill set that is usually not part of the traditional power systems engineering student's CV. The end goal of producing students who can run power flow and fault studies and use them for design and analysis is still achieved; however, students have a much deeper understanding of what the simulator is doing "under the hood."

In this paper, the authors detail the structure of the course, course topics, the term project, midterm assessments & checkoffs, and the final project.

Introduction

Power systems analysis is a field that tightly couples engineering, mathematics, and computer science. The key to accurate and insightful analysis is having accurate power systems models which require accuracy in all three of these fields [1]. Many power systems analysis courses focus a great deal on the engineering and mathematics side but do not focus as much on the computer science aspect. Instead, a simulator is used which this capable of performing the algorithms which solve for the power flowing through the equipment (transmission lines and transformers) or the currents experienced when a fault occurs. Courses taught using [2] as the textbook is given a complimentary version of the software, Powerworld to accomplish this [3].

The issue with this approach is that students do not get a good intuition in their results. Instead, they trust that the results produced by the output of the computer are correct. The authors hypothesize that the reason students lack this intuition is that they do not know what the algorithms are doing "under the hood" and that they can gain this intuition by writing the algorithms themselves.

The need for the use of computer methods programming was identified in [4], where the authors implemented a command line Unix based approach to teaching power. In [5], this work was expanded upon by integrating the Python programming language using Jupyter notebooks. It was shown that an effective way to teach systems analysis was using a flipped project-based learning approach in [6]. This technique was also applied to power systems analysis in [7]. The methods described here have been shown to be effective and when paired with software development provides a much deeper understanding the content taught in power systems analysis.

This paper details a novel approach to teaching a course in power systems analysis which couples engineering and math-based instruction with computer-science-based instruction.

Course Description

This novel approach to teaching power systems analysis is used in the course ECE 1774/2774 - Advanced Power Systems Analysis at the University of Pittsburgh. This is a second course in power systems analysis and is available to seniors and first-year graduate students. The course is taught using project-based learning where the students are given the semester-long project of developing a power systems simulator. Students work in teams of either two or three and work with their teammates for the entire semester. The project is broken up into six milestones which are checked off once completed. Students may attempt these milestones as many times as they would like but will only have them checked off when their simulators are functioning correctly for the given milestone. Similar classroom efforts have been shown to work in other courses such as the work presented in [8].

Students start by developing a simulator that simulates a very simple series circuit with a "transmission" resistor and a resistive load. This simple circuit assignment gets the students familiar with object-oriented programming and revision control using git and GitHub. This circuit is shown in Figure .

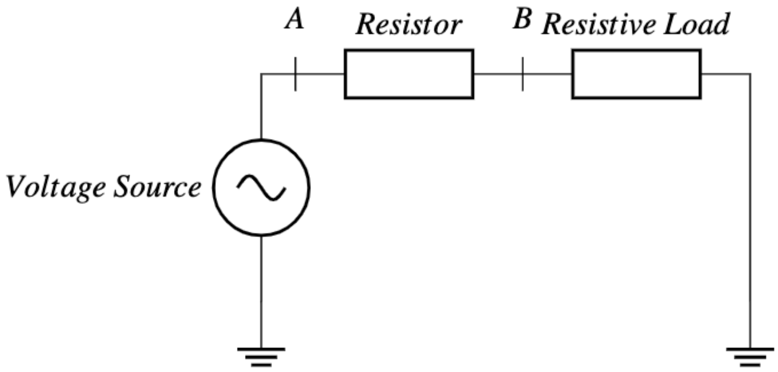
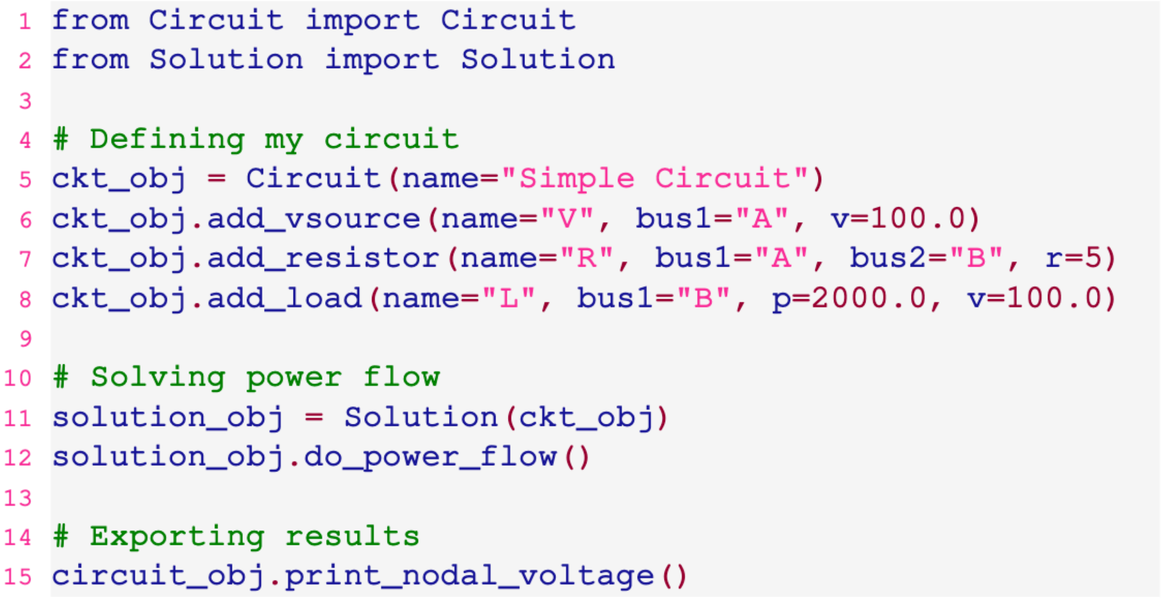


Figure 1: Simple Circuit

An example of the python code used to execute and solve this simple circuit is shown below. In this example the circuit is created, a voltage source is added, a resistive transmission line is added, a load is added, and finally, the system is solved. After attempting this, the instructors provide the students their solution so they can use it to learn how to program effectively. Students then write a short summary of what the instructors' code is doing and why.



```
from Circuit import Circuit
from Solution import Solution

# Defining my circuit
ckt_obj = Circuit(name="Simple Circuit")
ckt_obj.add_vsource(name="V", bus1="A", v=100.0)
ckt_obj.add_resistor(name="R", bus1="A", bus2="B", r=5)
ckt_obj.add_load(name="L", bus1="B", p=2000.0, v=100.0)

# Solving power flow
solution_obj = Solution(ckt_obj)
solution_obj.do_power_flow()

# Exporting results
circuit_obj.print_nodal_voltage()
```

After students complete the simple circuit assignment, they move on to the project milestones. The milestones used for the course are detailed in Table 1. Students start by developing the system admittance matrix (Y_{bus}) in Milestone 1. This requires students to properly model the network topology and the connected equipment. Milestone 2 requires students to set up and initialize the Newton-Raphson iterative algorithm. In Milestone 3, students iterate through the four steps of the Newton-Raphson algorithm until convergence is met. In Milestone 4, students implement faster solvers with lower fidelity. In Milestone 5, students develop the sequence networks required for performing fault studies. In the last milestone, students perform all fault types (line-to-ground, line-to-line, double line-to-ground, and symmetrical three-phase).

Table 1: Course Milestones

Milestone	Deliverable
1	Develop Power Flow System Ybus Matrix
2	Produce Power Flow Input Data, Jacobian, and Injection Equations
3	Develop Power Flow System Ybus Matrix
4	Var Limits and Different Solvers
5	Develop Positive, Negative, and Zero Sequence Networks
6	Perform Fault Analysis

Power systems, in their most basic form, are composed of generators, loads, transmission lines and transformers. This section details the models for each of these equipment types used for the project. A test system is given in the form of a one-line diagram with relevant topology, generator, transformer, transmission line, and load data. The mathematical models and code structure are both inspired by OpenDSS. OpenDSS is an open-source distribution system modeling and simulation software suite widely used by universities, consulting companies, electric distribution utilities, researchers, and other stakeholders worldwide [9].

System One-Line Diagram

A new system is developed every year for the course. The project used for the Spring 2022 semester is shown in Figure 2.

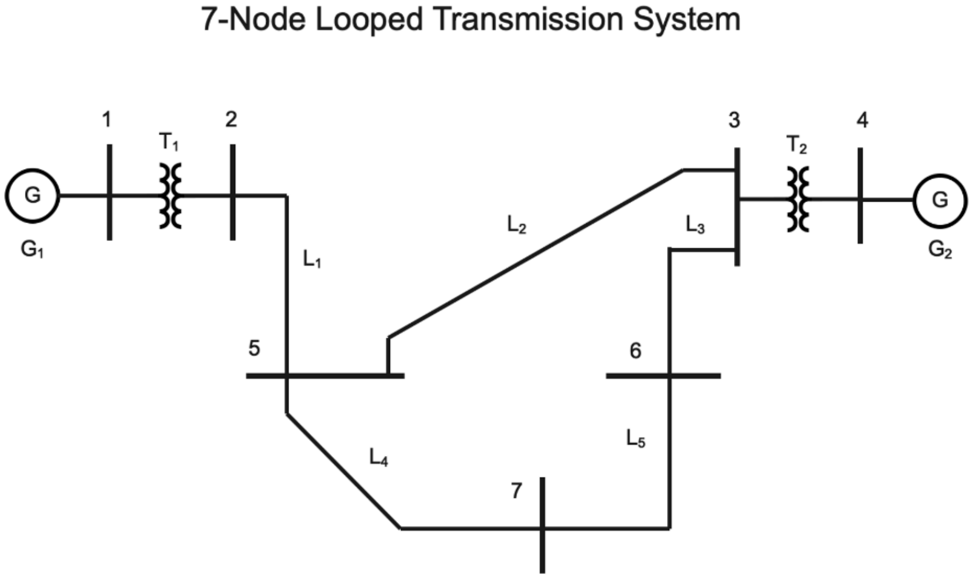


Figure 2: Seven Bus Test System for Project

The system is composed of seven buses. A bus is defined as any point in the system which is connected to two more pieces of equipment. The equipment in the system is composed of two generators, two transformers, five lines, and three loads.

Generator Model

The generator model has the nine user inputs described in Table 2. The generator supplies constant real power to the network at a fixed voltage. In practice, a generator has a control system that can either regulate the voltage of reactive power (Mvar). The generator has an Mvar maximum and an Mvar minimum which the generator's output cannot exceed. If the solution produces a generator Mvar output that exceeds the maximum or minimum values, then the exceeded (maximum or minimum) value is used for the generator's Mvar output and then the voltage is solved for, replacing the voltage setpoint.

Table 2: Generator Inputs

Input	Description
1	Power (MW) setpoint
2	Voltage setpoint
3	Reactive power (Mvar) maximum
4	Reactive power (Mvar) minimum
5	Positive sequence reactance (X_1)
6	Negative sequence reactance (X_2)
7	Zero-sequence reactance (X_0)
8	Winding configuration
9	Grounding impedance (Z_g)

The generator's positive, negative, and zero sequence reactance, along with its winding configuration and grounding impedance is only used during the calculation of fault currents.

Transformer Model

The transformer model has the nine user inputs described in Table 3. The transformer acts as a power conversion element in the system. This means that they transmit power from one bus to another bus. The purpose of a transformer is to transform voltage and current levels in the system to reduce overall systems losses.

Table 3: Transformer Inputs

Input	Description
1	Bus 1 voltage (kV) rating
2	Bus 2 voltage (kV) rating
3	Apparent power (MVA) rating
4	Impedance percentage (Z%)
5	Reactance to resistance ratio (X/R)
6	Winding 1 connection configuration
7	Winding 1 grounding impedance (Z_{g1})
8	Winding 2 configuration
9	Winding 2 grounding impedance (Z_{g2})

The transformer impedances as they are seen from winding 1 and winding 2 are calculated using the inputs defined in Table 3

Transmission Line Model

The transmission line model is a power delivery element and has thee models within itself. These models are the conductor model which contains the conductor material properties, the geometry model which contains the conductor geometric locations, and the bundling model which contains the geometry of the bundled subconductors. These models have a total of 10 inputs which are shown in Table 4.

Table 4: Transmission Line Inputs

Input	Description
1	Conductor diameter
2	Conductor geometric mean radius
3	Conductor resistance
4	Conductor ampacity
5	Phase a spacial position
6	Phase b spacial position
7	Phase c spacial position
8	Number of bundled conductors
9	Bundle spacing
10	Line length

The model produces the series resistance, series inductance, and shunt capacitance. The series inductance and shunt capacitance are used along with system frequency to produce the series reactance and shunt admittance.

Load Model

The load model is a simple one-terminal power conversion element that determines the real and reactive power injected into its respective bus. The load only has two inputs as are shown in Table 5

Table 5: Load Model

Input	Description
1	Real power
2	Reactive power

The model produces the series resistance, series inductance, and shunt capacitance. The series inductance and shunt capacitance are used along with system frequency to produce the series reactance and shunt admittance.

Simulation Model

The simulator's solution can be broken down into two types; power flow and fault study. Students are guided by the instructors to produce a program that is well constructed using object-oriented programming best practices. This can be seen in the class diagram in Figure 3.

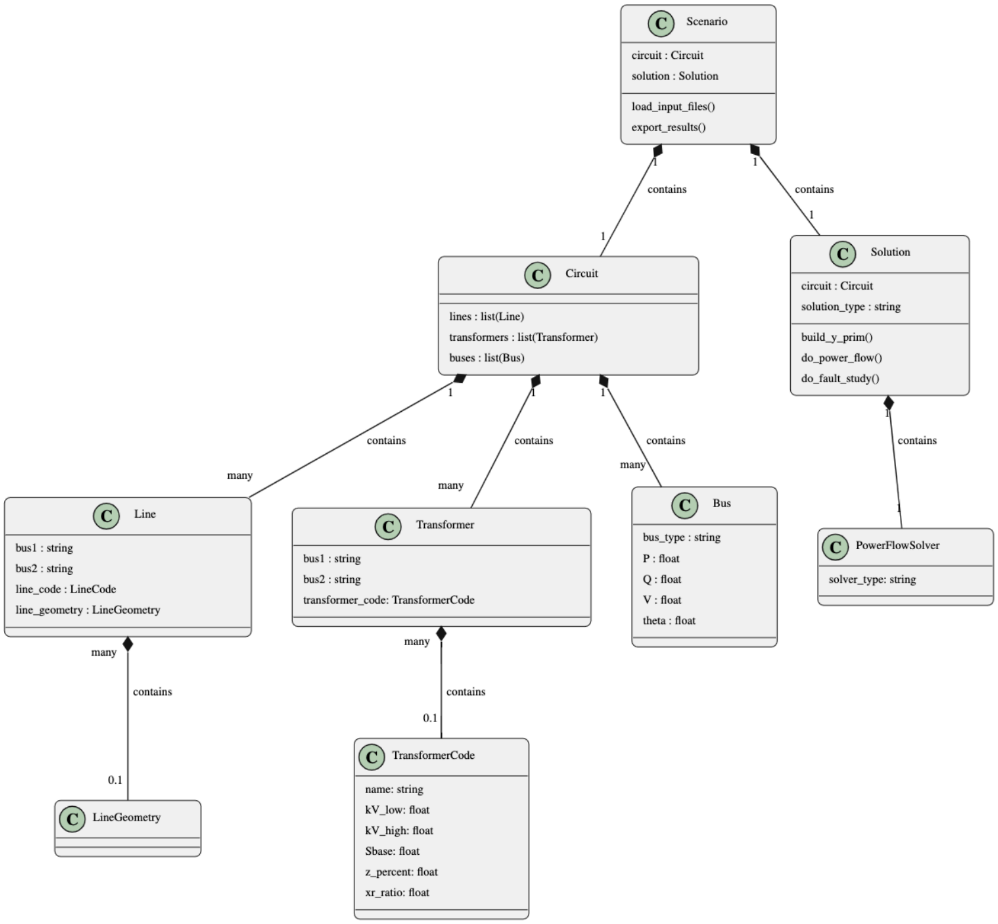


Figure 3: Class Diagram

Final Project

The final project is open-ended and allows students to implement a form of renewable generation into their simulators. Solar and wind are suggested but any form of generation not previously covered. As an example, for solar generation, the students are given the following instructions

- You are to integrate the solar PV system to into your system. This system is required to be connected to bus 7 at least 10 miles from the bus. You should use the same lines as in the project for the connection to the PV station.
- Solve the system for load flow with the PV connected. Use solve this using an average summer day, spring, fall, and winter day in the Pittsburgh area. Describe both performances for maximum PV output and for minimum in each case. Data is provided for 2020.
- Complete a full write-up of the research you did to create the model including citations. How you implemented it, assumptions made, and so on..
- Write a reflection on what could be improved in your model, what its limitations..etc.
- Use PowerWorld to verify your results. You will submit both the Powerorld model and your Python Code.

The system used is shown below in Figure 4

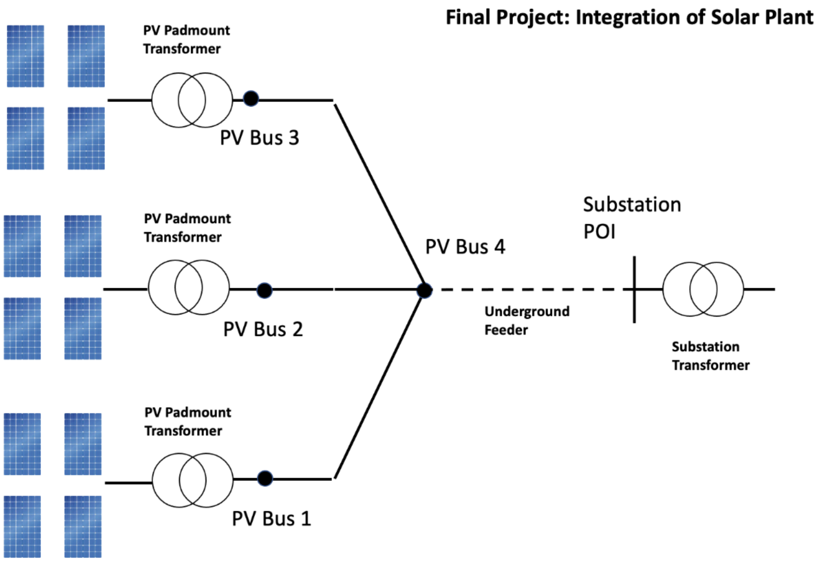
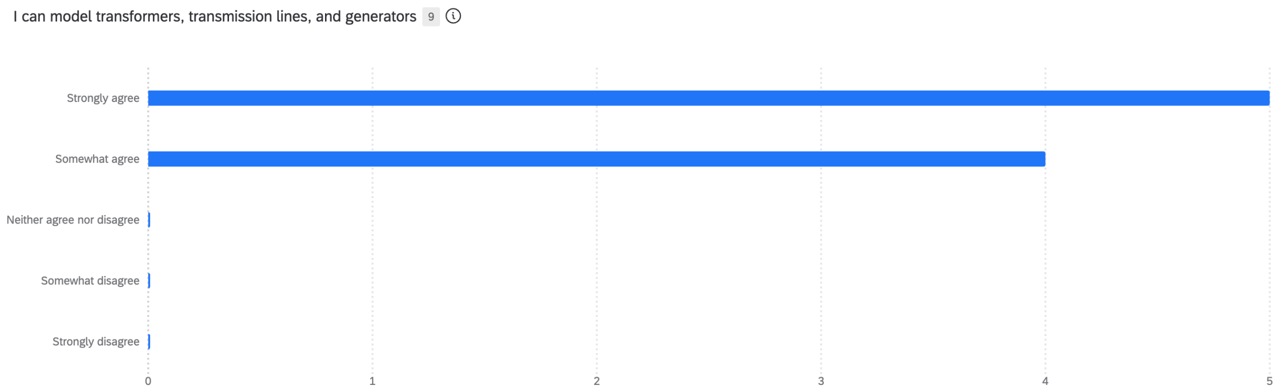


Figure 4: PV Plant

Indirect Assessment Results

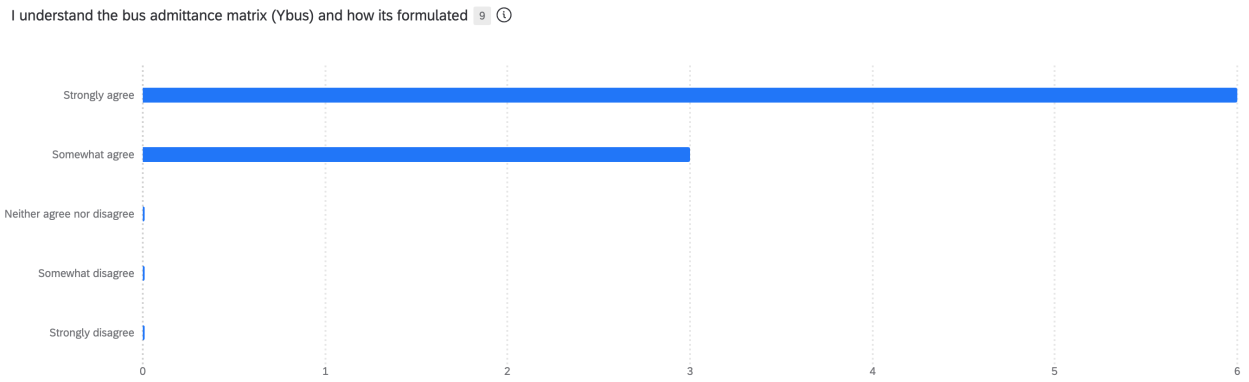
A total of ten students took the spring 2023 offering of the course. A Qualtrics survey was given to the students which performed an indirect assessment of the major course outcomes. This section details the results of this survey.

Question 1



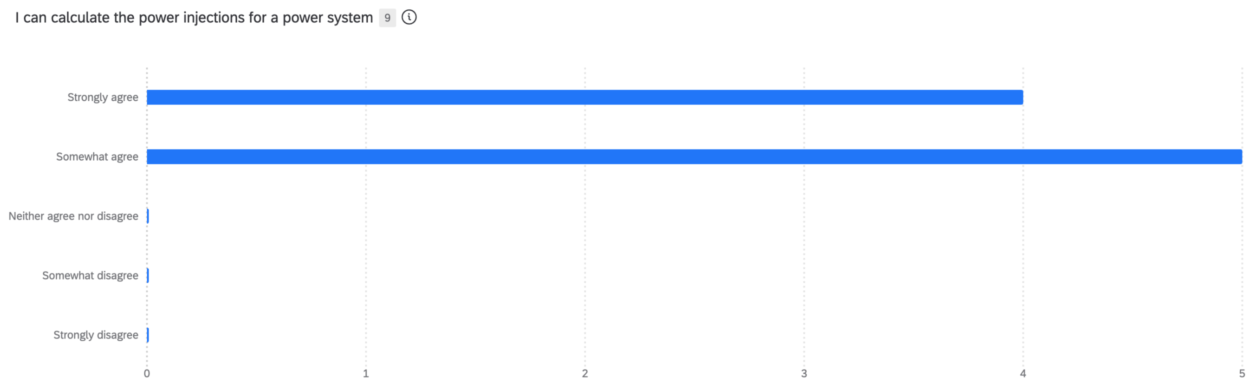
One of the major objectives of the course was for students to gain a basic understanding of power system equipment modeling. Five out of nine students strongly agreed, and four of nine students somewhat agreed that they could model basic power systems equipment.

Question 2



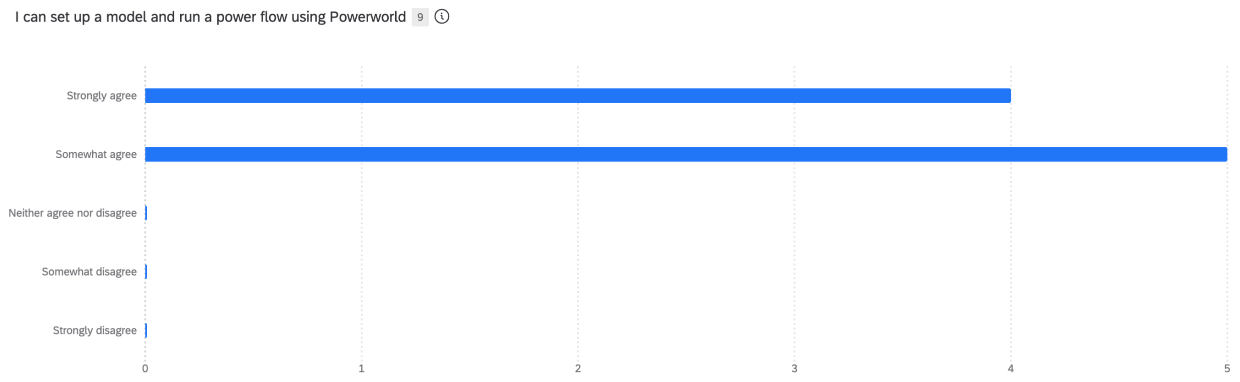
The key to performing power systems analysis is to set up a network admittance matrix. This is usually a difficult task for students. Six of nine students strongly agreed that they could perform this task and three out of six somewhat agreed. This was the most successful learning outcome.

Question 3



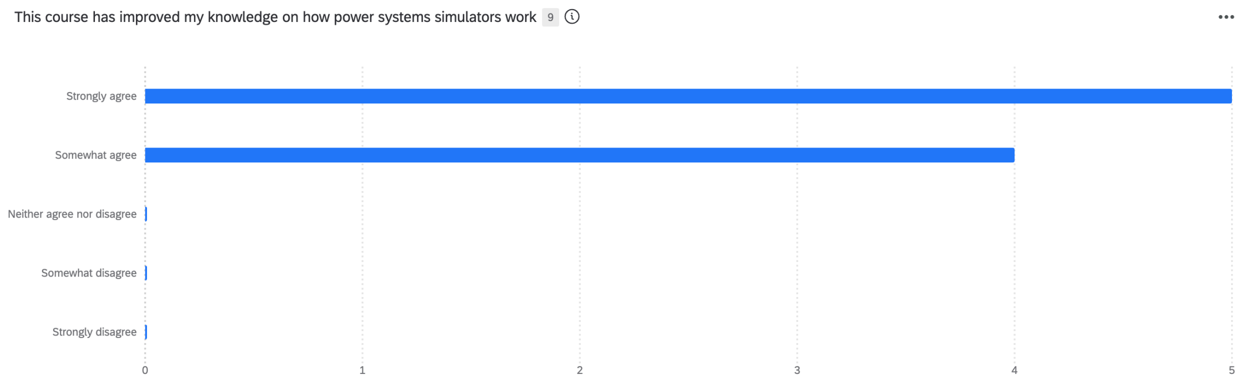
The power injection equations are the basis for how the Newton-Raphson algorithm works for power systems analysis. Four of nine students strongly agreed that they could perform this task and five out of nine somewhat agreed.

Question 4



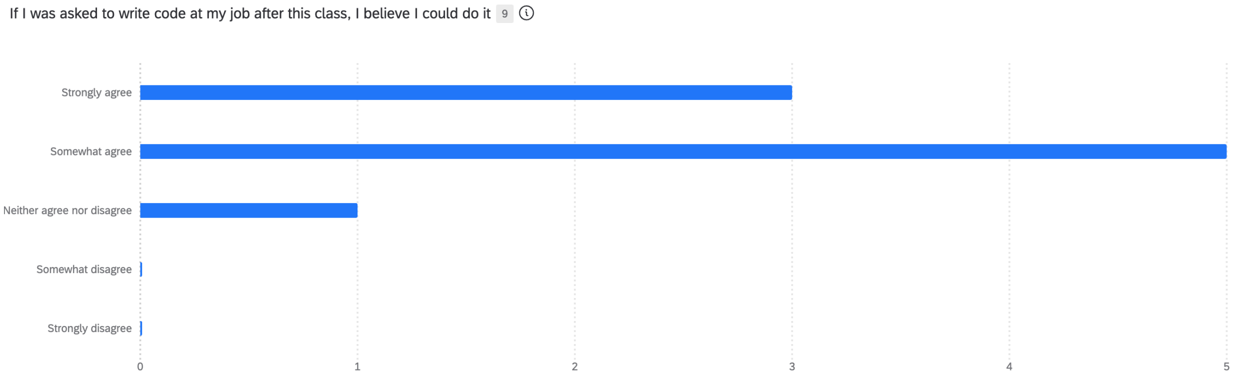
Another outcome was for students to learn how to use a commercial power systems simulator. Four of nine students strongly agreed that they could perform this task and five out of nine somewhat agreed.

Question 5



The main objective of the course was for students to gain an understanding of how power systems simulators work. For this question, five out of nine students strongly agreed that they understood power system simulation and four out of nine somewhat agreed.

Question 6



An extra bonus from teaching the course using this method was that students would pick up software skills. When asked if the students were confident, they could write code on a job, three of nine strongly agree, five of nine somewhat agreed, and one of nine was neutral.

Conclusions and Future Work

In conclusion, this course has been developed and adds a unique instance of a power systems analysis course. Students get to apply the computer science skills they pick up early in their engineering curriculum to a real-world problem which serves two purposes. Firstly, students must know they very ins and outs of the equations and algorithms which govern power systems analysis. This gives students a deep understanding of what the simulators do. Secondly, students pick up the very desirable computer programming skillset which is seen as a need all throughout the electric power industry.

The authors believe that this approach to teaching is both engaging and effective. The results of the indirect assessments shown in this paper back that up. Students either agreed or somewhat agreed that all learning objectives have been met, and only one student was neutral regarding their ability to use programming in their future employment. However, in this indirect assessment, the data shows that students were not as conformable computing the power injections equations and using the PowerWorld simulator as they were with the other main objectives. In addition, the instructors observed this to be true by talking and engaging with the students. This will be an area for improvement and stronger focus in upcoming offerings. One way to mitigate this is to focus on these topics using a very small system and hand calculations before moving to a larger system which requires a computer to perform the calculations.

In the future, the authors plan to collect data from future offerings of the course to improve upon what has been done. This data could be used to answer the question of whether this method of instruction is proven to be more effective than simply giving students a simulator to use.

In addition, the authors plan to release the course materials for other instructors to adopt in a future so that this method can have as big as in impact as possible.

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