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Computer Simulation Tools to Enhance Undergraduate Power Systems Education

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Abstract

This paper presents a review of software simulation tools relevant for use in undergraduate electrical power systems education. A study of the software packages is presented with respect to their utility in teaching according to the Cognitive Domain Hierarchy of Bloom's Taxonomy.

1. Introduction

In recent years a variety of factors have combined to place increasing pressure on the electric power industry; including increasing electrical energy demand, aging infrastructure, energy independence and security goals, and increasingly stringent environmental regulation. The use of smart grid technologies and distributed and renewable energy resources to meet these challenges as well as an aging workforce have resulted in a substantial training and recruitment need for the industry. Unfortunately, enrollment in power engineering programs in the U.S. is low, estimated at approximately 10% of electrical engineering majors [1], while university and industry support for power engineering programs has diminished [2]. At the same time, the electric power system is becoming increasingly complex and less deterministic due to introduction of new technologies, market deregulation, and increasing penetration of renewables and demand response programs. Therefore, the technical requirements for graduating students are constantly evolving from classic power engineering to include increased emphasis on topics such as information technology, power electronics, communication systems, and optimization [3]. Fortunately, this sea change was predicted and a variety of solutions to power education reform have been offered [4]-[6]. However, the need still exists to make changes in approaches to power engineering education in order to attract an increasing number of students and to increase focus on integrative elements of the grid [7]. Results of an NSF solicitation suggest that including the use of modeling and simulation tools providing instant feedback to students as the preferred teaching methodology can enhance the learning process as compared to classroom teaching [8], and an additional number of papers on the subject have supported this conclusion.

This paper begins with a review of the role of modeling in simulation in teaching undergraduate power engineering topics according to Bloom’s Taxonomy. An analysis of the published literature is then presented to identify best practices and knowledge-gaps. Using this analysis, the requirements for computer simulation tools for use in undergraduate education is developed in context of the power engineering domain. The paper concludes with examples of the use of simulation in modeling in a modern energy systems course at Purdue University and a survey of simulation tools used by electric utilities to connect the research to academic and industrial practice.

2. The role of computer simulation tools in undergraduate power engineering education

The mastery of STEM subjects requires that students engage in higher order learning hierarchical Cognitive objectives in excess of simple memorization, as described in Bloom's Taxonomy of Learning Domains [9], Fig. 1. In context of this taxonomy, the goals of undergraduate STEM pedagogy implementation activities are usually to develop instructional content at the Analysis level in which material and concepts can be understood in terms of their organizational structural within the discipline. While the M.S./M.Eng. degrees typically target the Synthesis or Evaluation levels, in which students can put parts together to form a whole concept and can make judgments about the value of ideas or materials within the subject, extending this approach to the undergraduate level can aid the development of life-long learning skills and concept retention [10].

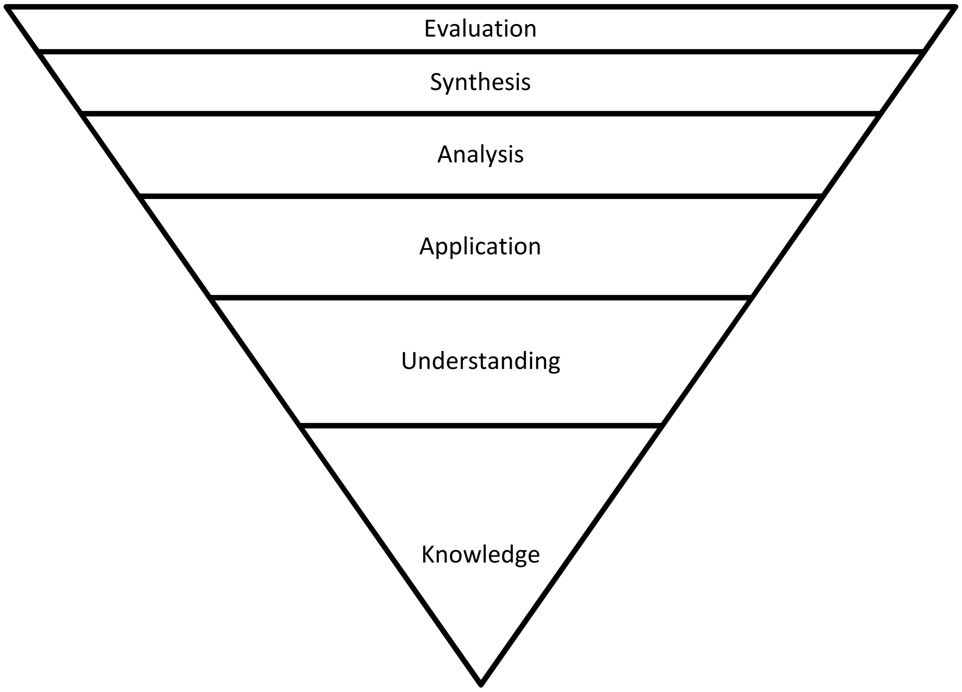


Figure 1. Cognitive Domain Hierarchy in Bloom's Taxonomy

Much research has been performed in the application of Bloom's taxonomy to engineering and technology course content as related to the efficacy of laboratory exercises to aid student learning through experience, and the importance of laboratories as part of engineering education is well established both generally [11] and for Power Engineering education [12]-[13]. However, two factors have combined to compound the challenge of providing quality lab curriculum: (1) changing motivations of faculty members, and (2) increasing complexity and cost of laboratory equipment [11]. Here, computers have opened the possibilities of simulation, automated data acquisition, remote control of instruments, and rapid data analysis and presentation, and universities are increasingly turning to the use of computer simulation tools to offset cost, reduce development time, and improve the laboratory experience.

Of course, instructional pedagogy development is not limited to only the improvement of student learning outcomes and may also include the following goals:

- Motivate students to self-directed learning and retention;
- Provide deeper understanding of fundamental principles through observation/experience;
- Reduce the amount of direct faculty involvement in course delivery;
- Allow for anytime/anywhere delivery;
- Promote limitless class sizes while promoting a “personal educator.”

Enabling technological advances in computing power, mass storage, software analysis and simulation techniques are the primary techniques available to educators to achieve these goals and have been identified as the most promising methods for developing and delivering improved electrical and computer engineering curriculum content [14].

We can therefore conclude that in context of Bloom’s taxonomy, computer simulation tools may add value to the student learning experience if they enable instructors to:

1. Shift the function of undergraduate courses from imparting content at the Knowledge level to instead improving the student’s learning process to reach the Synthesis and Evaluation levels.
2. Increase the amount of material or class size while continuing to achieve learning outcomes.

Despite previous work comparing the efficacy of hand-on, simulated, and remote laboratories [15]-[17], the debate regarding different approaches to course and laboratory instruction methods has not been settled in general and has not specifically addressed the unique requirements of electrical power engineering curriculum. The remainder of this section reviews the current research in the use of power system simulation software as an educational tool in engineering and engineering technology programs in an attempt to summarize the state of the current research and to develop a set of requirements for software packages to be used as instructional tools.

2.1.Efficacy of software simulation tools in power engineering education

Literature reporting on the efficacy of the use of power simulation software as a learning tool (Table 1) unanimously purport positive outcomes. Support for these results is drawn from end-of-term student reviews, comparison of student course grades with/without computer simulation, and in-depth student interviews. Of these, Milano et al. [24] specifically reports on the use of simulation software in an undergraduate power systems analysis course that results in a 14 percent increase in passing grades as compared to the same course offered without a simulation based laboratory component. Additionally, Temiz and Akuner [25] report a statistically significant benefit to the use of computer simulation tools for both student performance and knowledge retention over a six month period, though this article deals with three-phase rotating machines while all other articles deal with power system operations such as network modelling and fault analysis. Vanfretti and Milano [26], [27] study their use of the Power Systems Analysis Toolbox via a series of interviews with former students three years after completing an undergraduate course including PSAT to facilitate “deep learning. Although statistical analysis of the surveys was not included, the authors found that the use of simulation software triggered deep learning in students by allowing them to probe “what if” questions more readily. Additionally, the authors stress the need for the software to be open-source to enable the source code to be investigated and modified as an essential learning activity.

Despite the focus on the power engineering discipline, among the ten reviewed articles seven different software packages were used, not including custom toolboxes, and represent only a fraction of the commercial and open-source software packages available for power systems analysis. This lack of uniformity is further compounded by the use of different evaluation criteria in each study to measure the effectiveness of the use of simulation tools, suggesting that significant needs remain regarding the use of simulation tools for power engineering educational purposes including:

- Finding consensus in the best-of-class software.
- Developing clear learning objectives for simulation activities.
- Developing associated quantifiable metrics to evaluate learning objectives.
- Increasing size of data sets to allow for statistically verifiable conclusions on efficacy of software simulations as lab-tools.

Table 1. Comparison of Simulation Studies

Article	Software	Sub-Domain	Sample Size	Outcome
Doulai and Gosbel [18]	Custom	NM, PF, SC, FA, SA	Not stated	95% of students found practice “useful and favorable”. Course review scores above university-wide averaged.
Idowu and Omer [19]	MATLAB	ED	13	“The Visualization tool was very helpful in understand the economic dispatch problem.” Average student assessment: 4.2/5
Idowu and Omer [20]	Custom	PF, ED, UC	18	Visualization tool was very helpful in understanding the load flow, economic dispatch, and unit commitment problem.” Average student assessment: 3.8/5
Liao [21]	PSS/E, EMPT, Omicron,	PF, FA, TA, SA	Not stated	Understand essential concepts: phasor, power per unit system, bus admittance matrix. Average

	Python			student assessment: 4.8/5. Instructor Assessment 4.7/5
Liao et al. [22]	MATLAB	SG, P, T&D	Not Stated	Understand concepts related to: Smart grid- 4.8/5, 4.7/5 Electricity pricing - 4.8, 4.8 Distribution systems – 4.5, 4.6 Transmission systems – 4.8, 4.6 (Average student assessment, instructor assessment)
Lim [23]	Power World	SC, PF	24	“The instructional aids were beneficial.” Average student assessment = 4.88/5
Milano et al. [24]	PSAT (MATLAB)	PF, FA	Not Stated	Passing rate increased from 27% to 41%.
Temiz and Akuner [25]	Custom	M	80	Computer aided instruction increased average test scores by as much as 20 pts. Knowledge loss measured at 6 months is less, by 22 points, in students educated with computer simulation.
Vanfretti and Milano [26] [27]	PSAT (MATLAB)	Various	Not Stated	In depth student interviews support that computer simulation tools aid deep learning activities.
EC = Economic Dispatch, FA = Fault Analysis, M= Motors, NM = Network Modeling, PF = Power Flow, P = Pricing, SA = Stability Analysis, SC = System Components, SG = Smart Grid, TA = Transient Analysis, T&D= Transmission and Distribution, UC = Unit Commitment				

2.2.Requirements of computer simulation tools

A larger set of articles, including those from the previous section, were analyzed to determine the salient requirements for effective computer simulation tools for use in power engineering education. Table 2 summarizes this analysis. Largely, the requirements can be organized into three themes: ease of use, open source/proprietary, and applicability to various power-sub domains.

Table 2. Relevant Characteristics of Power System Simulation Tools for Educational Usage

Characteristic	Articles Supporting
3-D display	[23]
Animation of power flow	[19], [23]
Arrangement of components and function into a clear hierarchy	[20], [27]
Availability of real system data	[32]
Contouring onto maps	[23]

Coded in simple high level language	[35]
Creation/modification of models/solvers	[24], [27], [29], [33]
Editable source code	[24], [27], [35]
Enables comprehensive explanation of complex physical interactions	[8], [23]
Enables development of feel for I/O sensitivities	[8]
Explanation of algorithms	[19], [20]
Flexibility of analysis types	[27] ,[28]
Free or low cost	[19], [27], [29], [34], [35]
Graphical/user friendly interface	[8], [30], [33], [35]
Handle arbitrary time intervals	[29]
Instant (or near-instant) feedback	[8]
Interactive data entry	[8]
Interactive/visualized display of results	[8], [19], [20], [23], [30], [33]
Interface with external hardware/equipment	[31]
Object Oriented	[26], [29]
Per unit representation on one-line diagrams	[30], [33]
Robust solution	[28]
Simple and easy to use and learn	[23], [19], [20], [28], [33]
Simplifies complex calculations	[28], [34]
Transient and steady state analysis	[30], [33]
Utilized by industry	[23], [21]

Ease of use: For a simulation tool to add value to educational activities it must create deeper or more learning while not requiring inappropriate amounts of time to learn to operate, program for analysis, or interpret results. This is primarily achieve via graphical user interface to visually input systems using one line diagrams and well organized component libraries. Intuitively structured GUI interfaces can also simplify the running of the simulation analysis as well as setting boundary conditions and other simulation parameters. Output visualizations such as charting, plotting, and animation tools cam simplify the interpreting of results and aid student comprehension and allow for “what if?” analysis with little additional effort. Although commercial power analysis software packages, educationally focused packages, and more general technical computing software can all achieve these criteria, the complex analysis, models, and reporting required of real systems typically results in commercial products having little value in application as teaching tools, and when utilized, it is often achieved with a fair amount of “black box” operation from the perspective of the student where many parameters are left in a default state.

Open source versus proprietary software: The use of open source software presents several significant advantages from a pedagogical standpoint. First, open source software (OSS) is typically free, resulting in avoided cost to both the school and students. This has an ancillary benefit of increasing the likelihood that the students can obtain access to the software at locations other than the university, increasing the opportunities for students to utilize the programs. Of equal importance, OSS is editable and the source code is viewable. This allows educators to participate in the development of the OSS to create more strongly educationally focused programs and to develop tools/solvers as needed. Motivated students can examine the solver algorithms and understand them in relation to course activities. Finally, the use of OSS demonstrates to students that real world engineering problems are solvable without requiring proprietary tools, given the robustness and accuracy of modern power engineering OSSs.

Applicability to various power sub-domains: Due to the wide ranging analysis required of power system analysis, a variety of specific simulation tools exist to address subjects such as power flow, unit commitment, electromagnetic transients, etc. For the purposes of undergraduate power engineering, topics ancillary to power flow and voltage stability are often not typically treated in great enough detail to justify application specific solvers.

3. Modeling and simulation in a modern energy systems course

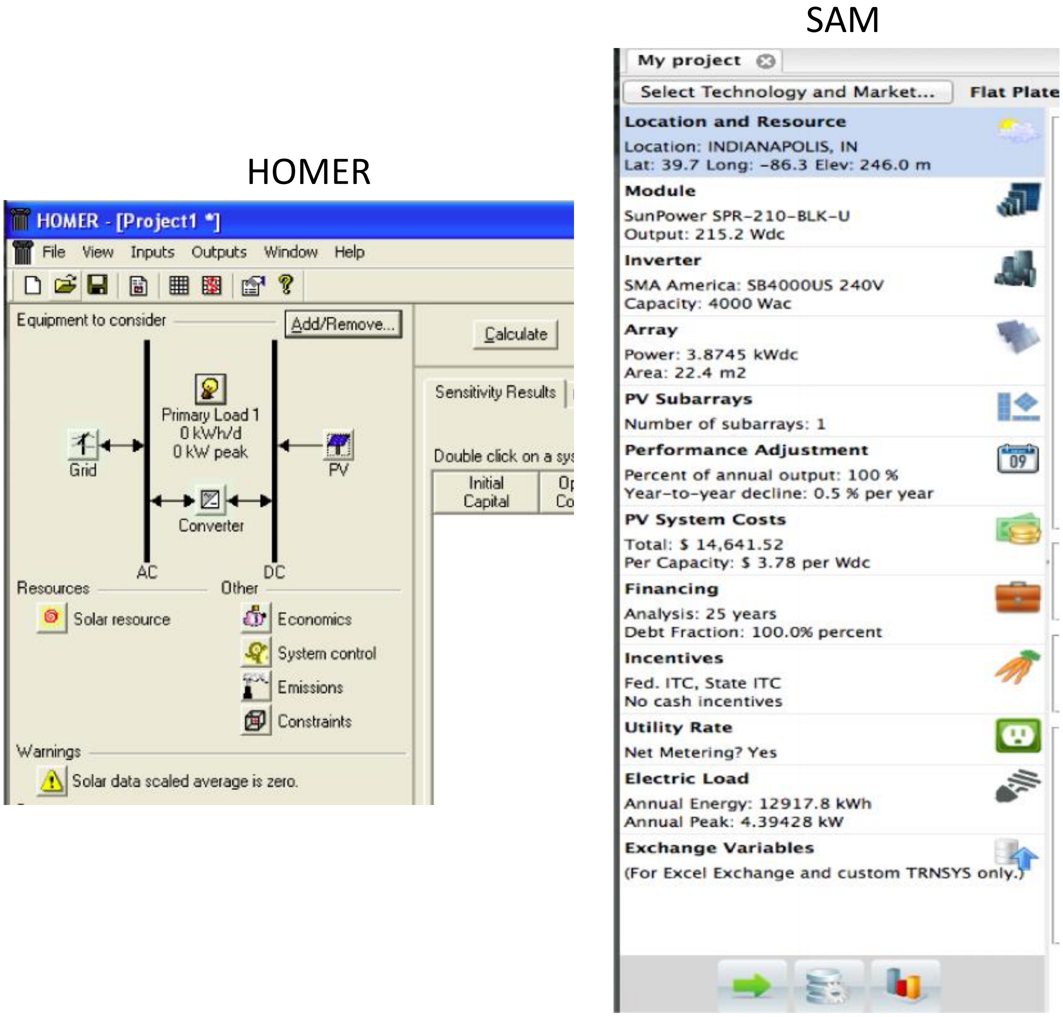
In this section we present tools used at Purdue University's College of Technology in a Modern Energy Systems course that demonstrate many of the requirements presented previously.

3.1.Use of electric power generation simulation tools

Two prominent free software tools for the simulation of power generation systems are the Hybrid Optimization Model for Electric Renewables (HOMER) [36] and the System Advisor Model (SAM) [37]. Additional tools from NREL can be found at [38].

SAM is intended as a replacement for HOMER. The SAM database of equipment specifications, such as solar panels, inverters, wind turbines, etc., is much larger and more updated than that of HOMER. As newer software, the graphs created by SAM are of higher quality. SAM also runs on both Windows® and MacOS® platforms, while HOMER only runs on Windows. Still, HOMER has some additional equipment, such as hydro, diesel, storage, and others, as well as a better GUI for laying out the equipment of a physical system. HOMER also seems to provide a lower-level access to simulation data within the tool, though SAM can integrate with software such as Microsoft Excel® for external data analysis. The selection of tool will vary by application.

Ease of learning: Both HOMER and SAM have extensive options to configure their simulations. Either tool can be daunting; however, HOMER has a very well developed documentation system where almost every option has mouse over help. Both tools will generate warnings for incorrect configurations that lead the user towards correction. In some cases, SAM's technical completeness in equipment parameters increases its learning curve, though this is a benefit for experienced users. Given a basic understanding of the power generation technologies utilized, undergraduate students can begin using either tool within a single lecture hour. This is important to encourage student engagement and foster self-learning activity. A sample configuration for a grid-tied solar photovoltaic array is illustrated in Figure 2.



Solar data scaled average is zero.

Location and Resource
Location: INDIANAPOLIS, IN
Lat: 39.7 Long: -86.3 Elev: 246.0 m

Module
SunPower SPR-210-BLK-U
Output: 215.2 Wdc

Inverter
SMA America: SB4000US 240V
Capacity: 4000 Wac

Array
Power: 3.8745 kWdc
Area: 22.4 m2

PV Subarrays
Number of subarrays: 1

Performance Adjustment
Percent of annual output: 100 %
Year-to-year decline: 0.5 % per year

PV System Costs
Total: $ 14,641.52
Per Capacity: $ 3.78 per Wdc

Financing
Analysis: 25 years
Debt Fraction: 100.0% percent

Incentives
Fed. ITC, State ITC
No cash incentives

Utility Rate
Net Metering? Yes

Electric Load
Annual Energy: 12917.8 kWh
Annual Peak: 4.39428 kW

Exchange Variables
(For Excel Exchange and custom TRNSYS only.)

Figure 2. A simple grid connected solar power system in HOMER and SAM.

HOMER focuses on a visual system configuration. Each component is a button that opens a separate window for entry of parameters. Simulation parameters are also buttons in the Resources/Other section, with warnings below. In contrast, SAM displays more information in a vertical set of tabs, but lacks a physical model by which to visualize the power system. It is expected that beginning students would benefit more by having a visual model with which to interact. Clicking in one of SAM's tabs brings up a configuration window as in HOMER, but with more options for advanced users. Both include many parameter fields populated with default values, which helps students start quickly while illustrating real world quantities. While HOMER includes a broader range of equipment types, SAM's database has more examples that are up to date for supported equipment.

Conveyance of concepts: HOMER and SAM allow a user to experiment with different configuration parameters, as well as different system configurations in general. This demonstrates the effect of such changes to students, which can be observed in either tool via numerous surface plots. Beginning students also gain an understanding of needed equipment to complete a configuration and how that equipment is interconnected, especially in HOMER. When exploring the ability of a system to meet certain power loads and the economic feasibility of system configurations, students implicitly gain additional understanding of concepts required in evaluating real world systems. In fact, HOMER and SAM can follow the student into practical application for career projects.

A very good evaluation of the use of HOMER as an educational tool is presented in [39]. Both a discussion of the HOMER's capabilities and its use by instructors and students are examined in detail. The results conclusively demonstrate HOMER's effectiveness in the classroom. SAM is expected to have similar success, based on the same simulation engine.

Effectiveness as real world tools: As discussed, HOMER and SAM are capable tools that are designed to simulate real world systems and environments. SAM specifically incorporates the use of TMY weather information for many locations. Each of these can perform an hourly, or higher granularity, annual analysis spanning many years including equipment and maintenance costs, load forecasting and dispatch strategies, and changes in power and fuel costs over the life time. Each can summarize these results in a variety of surface plots and automatically generated reports. HOMER itself has over 98,000 users in 193 countries [36]. Being much newer software, SAM is rapidly gaining in adoption [37]. A specific evaluation of SAM in four case studies demonstrates its accuracy in real world applications [40]. The applicability of HOMER has been discussed in [41] and examined in case studies [42] and [43] as well.

Notes from Modern Energy Systems: HOMER was utilized to perform multiple student lab experiments in an undergraduate energy systems course at Purdue University College of Technology, Department of Electrical and Computer Engineering Technology during Fall 2013. Students were assigned a real world problem requiring the development of a power generation system capable of meeting a given load under certain conditions. Students were required to evaluate life cycle costs and environmental impacts, in addition to necessary power requirements. In each experiment, the student gained experience using a different power technology, e.g., solar, wind, batteries, and documented their findings in a report supported by data and plots from the HOMER tool. An informal survey following these labs indicated that the students enjoyed using the tool as it afforded them a visual, hands-on learning approach. The free availability also allowed students to run the software on their computers to work on their own schedule and pace.

3.2.Use of electric power flow simulation tools

PowerFactory [44] is a power system simulation software tool for the creation and analysis of simple or complex models of the electric grid using a user-friendly GUI interface for 1-line diagram creation using, drag and drop component placement and expansive component toolboxes. All components have properties that can be configured as needed. For example property a bus bar can be configured for: type (AC or DC), phase technology (3-phase, 2-phase, 1- phase etc.), and line to line voltage amongst other parameters. The analysis that can be done using power factory varies from simple power flow analysis to complex transient analysis during a fault.

Notes from Modern Energy Systems: PowerFactory was used in the labs for students to teach basic power system behavior, changes in the network due to the introduction of renewable energy sources and the effect on line voltages due to loading. A simple power system, shown in Figure 3, was modeled and analyzed for power flow. The starting point of the network is an external grid representing the system beyond the area of interest, and is characterized with starting point parameters. The network under analysis consists of different voltage levels (33kV, 12.47 kV, 4.16 kV and 208 V) and a variety of components connected at these levels, including transformers, motors, different types of loads, static var compensators, voltage regulators and a wind generator.

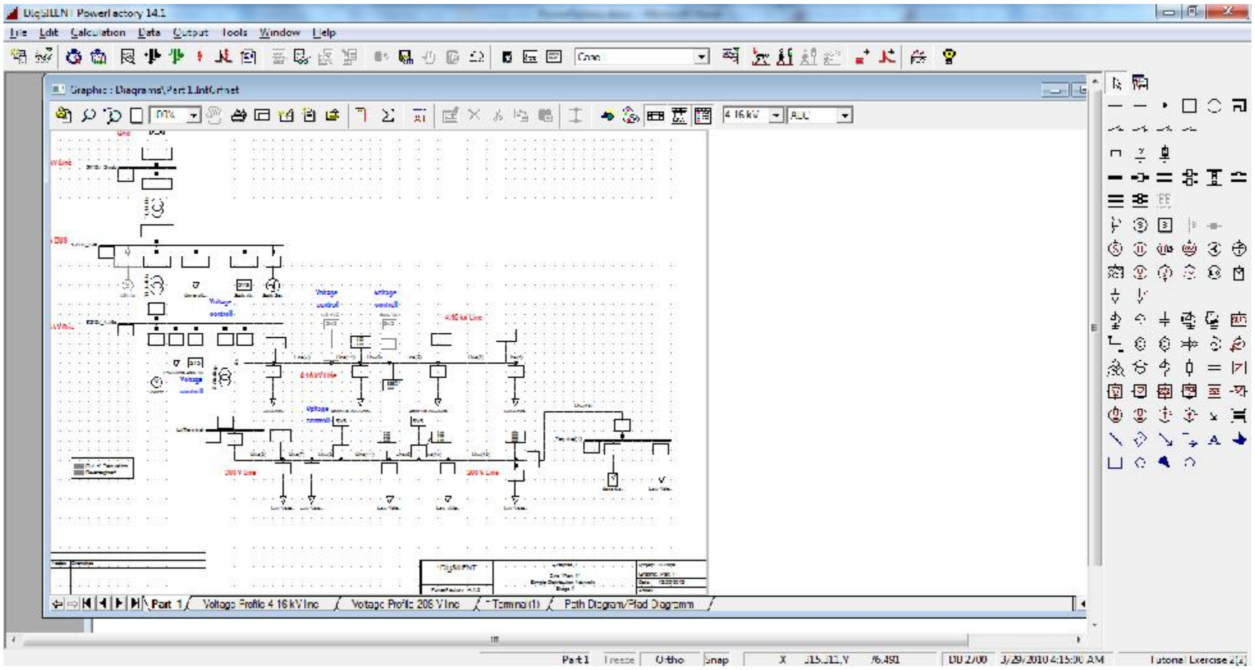


Figure 3. Simple power system modeled in PowerFactory.

Figure 4 shows the data obtained from the power flow study. Boxes connected to each component shows power flow data including voltage, active power, reactive power, and phase angle. More data can be added as needed.   Color variation shows the loading level of the grid, making for easy evaluation by students. For example, the orange in Figure 5 shows more than 80% loading in the system.

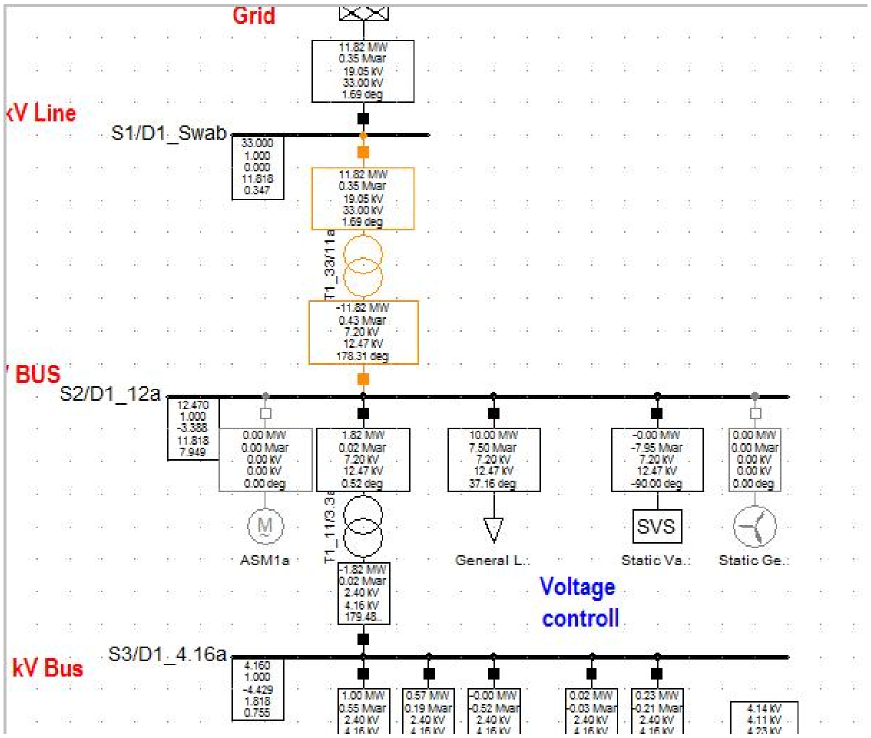


Figure 4. Power flow data showing system loading.

Power factory was also used to investigate the effect of renewable sources in the network by connecting a wind farm to the grid. Addition of the wind farm on the overloaded branch in Figure 4 caused the transformer loading to reduce to within system limits, however the wind plant itself becomes overloaded, a condition that is indicated visually in PowerFactory by highlighting the component in red for easy identification. Students can use this visual information and the numeric parameters calculated to re-design the system to operate properly.

4. Industry Survey Results

Ostensibly, many students entering the power engineering field as engineers will be employed to perform system simulations. To better understand current industry requirements and evaluate them for suitability as educational tools, a modeling and simulation survey was distributed and completed by 17 of the jurisdictional utilities in the state of Kentucky. The following section summarizes the collected responses to this survey.

11 utilities reported utilizing modeling and analysis software in an “offline” mode (not utilize dynamically changing distribution operating conditions) to perform “what if” power flow calculations. Nine of the responding utilities utilize Milsoft Windmil for Distribution System Modeling and Analysis, one uses Alstom and one uses Stoner Software. Note that there was no

overlap between software packages utilized for educational purposes and those utilized for commercial purposes, indicating strongly divergent requirements. The following table summarizes supported sub-functions utilized by industry, and can be utilized to add industry relevance to laboratory topics pursued in courses, even if performed using different software packages.

Table 3. Number of Utilities with Supported Modeling and Simulation Sub Functions

Sub Function	Number of Utilities Supporting
Modeling of impacts of the low-voltage distribution system on transmission/sub-transmission	2
Modeling of distribution circuit connectivity	6
Data Management between legacy databases	6
Modeling of distribution nodal loads for kW	5
Modeling of distribution nodal loads for kVA	5
Modeling of distribution circuit facilities	5
Distribution power flow	5
Evaluation of transfer capacity of tie switches	5
Power quality analysis	3
Loss analysis	5
Fault analysis	6
Evaluation of operating conditions	3

5. Conclusion

This paper has presented a comprehensive review of the available literature describing the efficacy of simulation software for use in electrical power engineering, with a particular focus on traditional laboratory activities. Although the literature generally supports the use of such tools to be an effective pedagogical approach, no experimentally verifiable evidence supports these claims, which are instead largely drawn from qualitative assessments performed at completion of a power systems analysis course. To quantitatively evaluate such claims, we suggest the development clear objectives for simulation activities, coupled with associated quantifiable metrics to evaluate learning objectives that are collected in data sets of sufficient size to allow for statistically verifiable conclusions. Regarding the features of software packages most beneficial to a college course, we find that little is actually required: easy to use with small learning curve, open source, and applicability across various power-sub domains. In particular, we find that choosing software based on the desire to match the tools used in industry is not conducive to student learning as it cannot meet these base-level requirements.

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