

New Resources for Undergraduate Power Systems Laboratory

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Abstract

Development of the smart grid and renewable energy generation has been substantially changing the undergraduate education in fundamental power systems. Many new programs in power systems engineering are focused on cross-disciplinary for students not only in traditional electrical engineering, but also in non-electrical engineering, such as computer and information sciences, telecommunication and systems engineering. It is a challenge for these new programs to provide laboratory training of undergraduate students because of the restrictions of physical experimental resources in a power systems laboratory. This paper discusses the new resources for undergraduate power systems laboratories by including the big data generated from smart grids and online information and data of power grid operation.

Introduction

Recent years, the development of the smart grid and renewable energy generation has been substantially changing the undergraduate education in fundamental power systems. While traditional education in fundamental power systems is focused on general-purpose power components such as electric machines, many new programs in power systems engineering are focused on the smart grid and renewable energy generation which are found on advanced computing, telecommunication and information sciences. These new programs in power systems engineering pay more attention on cross-disciplinary. They are attractive not only for students in traditional electrical engineering, but also for students in non-electrical engineering, such as computer and information sciences, telecommunication and systems engineering. Although traditional power engineering program is still important in a number of prestigious universities, new power systems programs will have better opportunities in many universities with less traditional experimental resources. Since laboratory experiments are an important part of undergraduate education in fundamental power systems, this paper will discuss some new resources of power systems laboratories.

Traditional power systems laboratories are strongly dependent on the physical components and simulation software. Power components such as power transformers, electric machines, passive loads are standard physical components which are used for students to get experimental training in component level. For system level training, power system simulation programs such as Power World and PSCAD are often the only tools for students to obtain experimental training in a power systems laboratory. Such a laboratory is not effective for new power systems programs. For most universities, it is not realistic to set up a power systems laboratory with necessary

physical grid-level equipment, enough professional technical support and necessary training for students because of the restriction in laboratory funding and program curriculum. Although power system simulation programs are widely used in undergraduate education of power grids, simulation is not enough for students to obtain experimental experience.

In this paper we present the potential industrial resources which can be used for power systems experiments in undergraduate education. The contents are organized in the following sections: (1) developments in power systems laboratories, (2) digitization of power grids, (3) online information and data of power grid, (4) student learning outcomes, and (5) conclusions.

Developments in Power Systems Laboratories

A systematic review about laboratory education in contemporary power engineering was presented in a panel session of IEEE Power Engineering Society Summer Meeting in 2000 [1, 2, 3]. The work presents the role of laboratory education in power engineering, the experience of the classical power systems laboratory. To meet the requirements of future power systems engineering, the authors pointed out the important capabilities of a future power systems laboratory: (1) to support distance learning courses, (2) to run in open lab fashion, and (3) to target multi-dimensional engineers instead of only classical power systems engineers.

A virtual laboratory for power systems is built on advanced computer simulation, animation and visualization. As discussed in [1] and [3], a simulation-based virtual laboratory have significant advantages compared to traditional physical laboratory in respects of safety, information representation and experiment flexibility. However, the simulation is restricted by virtual environments and non-ideal effects of simulation models. These restrictions make it difficult to replace the physical laboratory with a virtual laboratory. Development of hands-on capability for undergraduate students in electrical engineering is another important reason to keep the physical laboratory.

The role of laboratory in the education of modern power systems is also discussed in [4] for both lecture-based education and project-based learning. This work presents details about the assessment methods for different methods of teaching.

The works [5] and [6] present the solutions of power engineering laboratories which are suitable for small undergraduate institutes with economic and space restrictions. A unified power engineering laboratory is proposed in [6] which can be used for various experiments related to power systems, power electronics, and energy conversion.

Different approaches of teaching laboratory classes in electrical engineering are discussed in [7]. The author proposed a vertically integrated approach to hands-on laboratory experimentation for teaching PV systems. In this approach students get the experience of designing and building each part in a PV system.

One important renovation for power systems laboratories is the computerization of power system experiments. Equipped with LabVIEW-based virtual instruments, or Matlab/Simulink program

with a DSP-based real-time data acquisition and control [9], the computerized experimental systems make it possible for students to complete the assigned experiments by using a computer. The students can even complete the system simulation and system experiments with the same computer so that they can compare the simulation results and experimental results easily.

An online power laboratory was presented in [8], which is an online remote laboratory and can be shared among universities. The laboratory was developed for renewable generation experiments.

Digitization of Industrial Power Systems

One important feature of the smart grid is digitization of power grid. Smart meters, SCADA systems, PMUs, micro-PMUs, and protection relays collect energy and power related data from generation, transmission/distribution, and customer loads continuously and generate huge data records. On the one hand, it is the new challenge for power systems education to provide cross-disciplinary power system engineers that can comprehend, design, and manage digitized power systems [10, 11]. On the other hand, it is also a new opportunity for educational power systems laboratories where students may utilize a digitized power grid or a virtual copy of a power grid for experimental study and analysis.

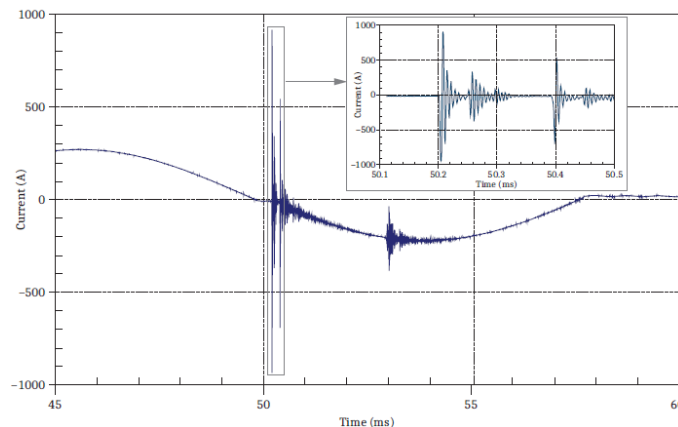


Figure 1. Measured current waveforms of SEL-T400L Time-Domain Line Protection [16]

Early digitization of power systems, including power generation, transmission and distribution was implemented with supervisory control and data acquisition (SCADA) systems. SCADA is a general-purpose control system architecture that uses computers, networked data communication and graphical user interfaces for high-level process supervisory management, and uses real-time units (RTUs) such as programmable logic controllers (PLCs) to interface with the process plant or machinery. Power systems are traditional SCADA applications where the sensor signals are digitally recorded every 2 – 4 seconds. With the development of smart grid technology new digital meters such as smart meters and phasor measurement units (PMUs) are getting widely used in power systems. Smart meters collect energy consumption records of customers every 15 minutes which may help for the optimization of energy forecasting model. PMUs and micro-PMUs for transmission and distribution systems measure GPS time-referenced voltage and

current phasors (magnitudes and phase angles) at up to 120 records per second. Different from traditional SCADA in power systems, PMUs and micro-PMUs with GPS-time stamped phasor records are suitable for wide area measurement system (WAMS). The applications include wide area monitoring, real-time operations, improved accuracy of models, and forensic analysis [13]. The practical PMUs are implemented in either independent PMU devices [16] or relay-integrated features [15]. Inside such devices, the GPS time-stamped data sampling rates are up to 1 Mega Samples per second at 18-bit ADC resolution [16]. An example of such recorded data is shown in Figure 1 which provides measurement of time-stamped current waveform with disturbances.

PMUs and micro PMUs provide digital records of both steady-state and dynamic performance of a power grid. Without bringing the physical system into a laboratory, students can study the digital copy of a power grid operation for understanding the behavior of a practical grid-level power component, for instance a power transformer in a substation, or a part of power grid. If the precision of measured data is high enough, it is possible for students to identify parameters of a power transformer, a transmission/distribution line, or a part of a power grid. As an example, we can identify the parameters of a power transformer by using measured phasors without traditional open-circuit and short-circuit tests. Figure 2 shows the per-unit per-phase equivalent circuit of a power transformer. The shunt- and series-parameters can be calculated with the measured voltage and current phasors of the power transformer as:

$$R_C + jX_M = \frac{\vec{V}_1}{\vec{I}_1 - \vec{I}_2} \quad (1)$$

$$R_{EQ} + jX_{EQ} = \frac{\vec{V}_1 - \vec{V}_2}{\vec{I}_2} \quad (2)$$

where \vec{V}_1, \vec{V}_2 and \vec{I}_1, \vec{I}_2 are measured voltage and current phasors in per unit.

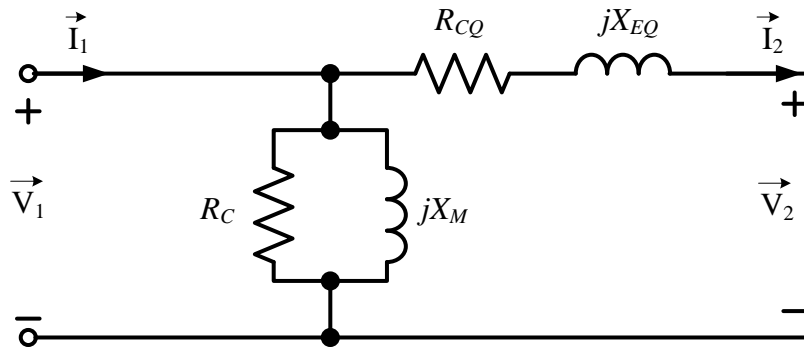


Figure 2. Per-unit equivalent circuit of a power transformer

Online Information and Data of Power Grid

Electric utility industry is becoming more and more transparent to public with the availability of the real-time and historic operating data on websites. The important websites providing the information and data of electric energy and power grid are maintained by (1) U.S. Energy Information Administration [17], (2) all Regional Transmission Organizations

(RTS)/Independent System Operators (ISO) [18, 19], and (3) electric utility companies. Although there are significant differences among websites maintained by different RTOs/ISOs, they generally include information and data of real-time demand, supply, and prices. These information and data can be used for experimental purposes in a power systems laboratory, which will help students to develop the capability to collect and understand the information and data of the nationwide energy and power system, regional power grids, and local electric utilities. Working with the data provided by these websites, students will also obtain practical training in energy/power big data analytics, an emerging key skill of electricity workforce [10, 11].

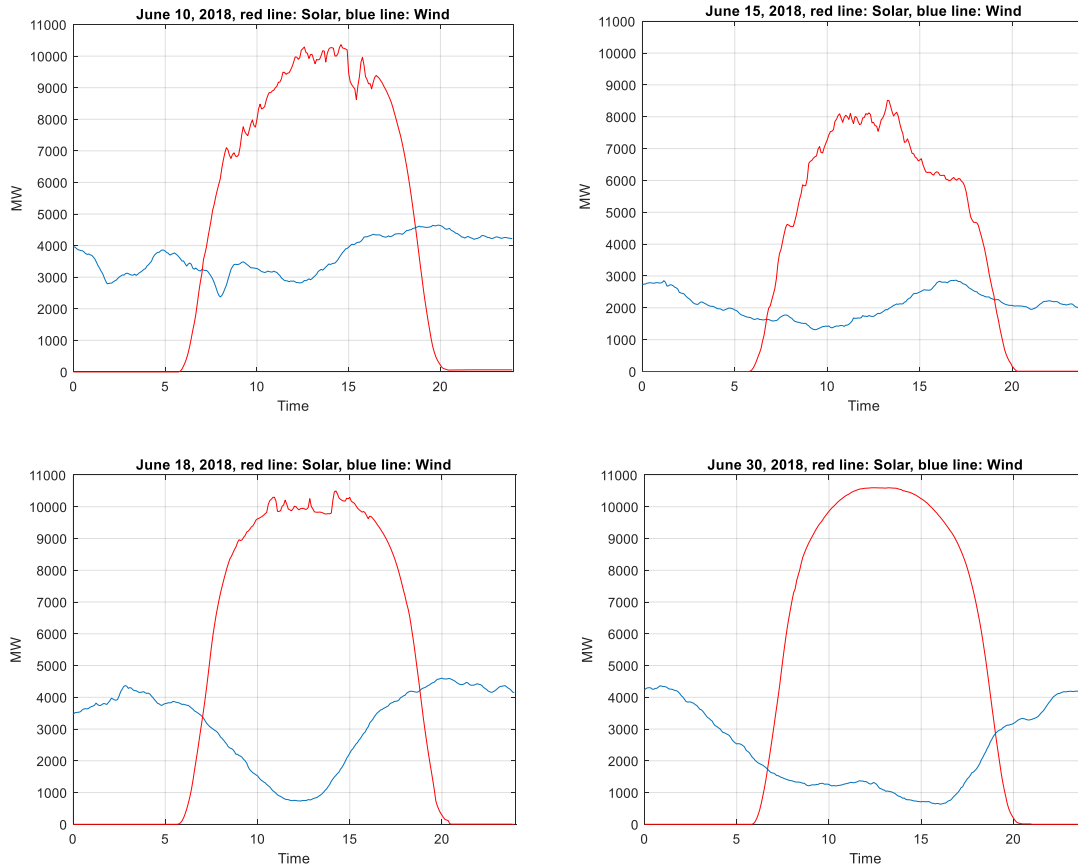


Figure 3. Four days records of solar and wind power generation in June 2018 provided by CISO

As an example to use the online resources of information and data of a power grid, we downloaded the records of renewable energy generation of four days in June 2018 provided by California Independent System Operator (CISO) [18]. We used Matlab to draw solar and wind power generation on each day as shown in Figure 3. The time is 24 hours. In power grid managed by CISO, renewable energy generation can cover up to 50% electricity demand during a day, in which up to 75% is solar power generation. Therefore, the data study of the renewable energy generation records provided by CISO is helpful for student to understand the impact of renewable energy generation on the operation of a practical power grid, the effect of weather on the renewable power generation, and the current integration of renewable energy in CISO power grid.

As shown in Figure 3, the records of solar and wind power generation on June 30, 2018 is quite stable. The weather was good for solar power generation during the day. The solar power generation changed smoothly with the peak power up to 10.5 GW and without obvious disturbance. The wind power generation was high (up to 4.3 GW) in the early morning and the late evening, and became low (about 1 GW) during the day. The records on June 18, 2018 shows some disturbance of solar power generation from 11:00 am to 2:00 pm. Compared to June 30, the records on June 15 shows a significant drop (more than 2 GW) of solar power generation during the day while the wind power generation was relatively high (about 2 GW) during the day. The records on June 10 shows some disturbances in solar power generation during the day while the wind power generation kept quite high (from 3 to 4 GW) during the whole day. These records present the effects of weather on the renewable energy.

Figure 4 shows the records of demand and net demand of CISO power grid on June 30, 2018. The net demand is the demand minus solar and wind power generation. Because of solar power generation, net demand dropped significantly compared to the demand during the day. The red curve of the net demand is referred to as the so-called “duck curve” for its distinctive shape, which shows the significant impact of solar power generation on the CISO regional power grid.

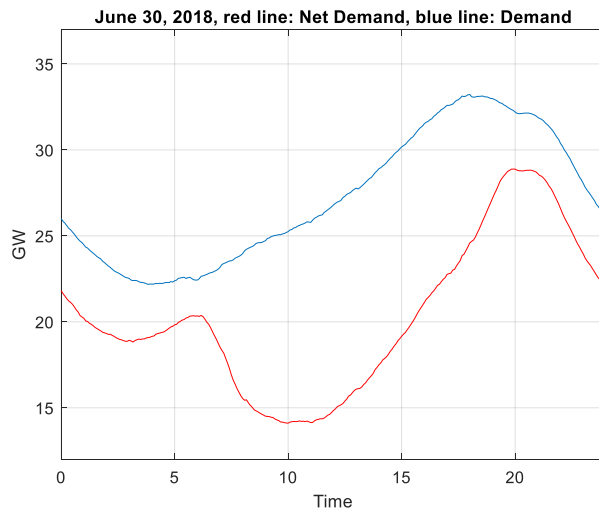


Figure 4. CISO records of demand and net demand of electricity on June 30, 2018

Student Learning Outcomes

The new resources discussed above will enhance the ABET student learning outcomes in (a) an ability to apply knowledge of mathematics, science, and engineering; (b) an ability to design and conduct experiments, as well as to analyze and interpret data; (e) an ability to identify, formulate, and solve engineering problems; (h) the broad education necessary to understand the impact of engineering solutions in global, economic, environmental, and societal context; (j) a knowledge of contemporary issues; and (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. The value rubrics and key performance indicators are listed in Table 1.

Table 1 ABET Student Outcomes, rubrics and student artifacts

Student Outcome	Value Rubrics/ Key performance indicators
a. an ability to apply knowledge of mathematics, science, and engineering	<ol style="list-style-type: none"> 1. An ability to apply complex number, phasors and Nodal equations in AC power circuit analysis 2. An ability to use singular value decomposition, regression analysis, and time series analysis in data analysis
b. an ability to design and conduct experiments, as well as to analyze and interpret data	<ol style="list-style-type: none"> 1. An ability to design data analytics for assigned experiments. 2. An ability to collect data and conduct experiment 3. An ability to analyze and interpret experimental data to reach conclusions
e. an ability to identify, formulate, and solve engineering problems	<ol style="list-style-type: none"> 1. An ability to clearly define and formulate the problem 2. An ability to complete data analysis with reasonable tools. 3. An ability to apply theoretical concepts to evaluate the experimental results
h. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context	<ol style="list-style-type: none"> 1. Having broad knowledge to assess the impact of energy and power engineering in a global context 2. An ability to apply economic considerations to arrive at cost effective engineering solutions 3. An ability to analyze the environmental and societal impacts of engineering solutions
j. a knowledge of contemporary issues	<ol style="list-style-type: none"> 1. Understand smart grid, renewable energy generation and energy storages in power grid 2. An ability to use online information and data of energy and electrical grids 3. Having knowledge of communication network and cybersecurity in power systems
k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice	<ol style="list-style-type: none"> 1. An ability to use advanced computing and network communication to conduct power systems experiments, including design and simulation. 2. An ability to use PMU data for parameter identification and system analysis 3. An ability to use tools for big data analytics to analyze the data of power grids

Conclusions

Digitization of power grid and online information & data provide tremendous new resources for undergraduate power systems laboratories. Wide-area installed PMUs and micro PMUs generate big data of GPS time-stamped measurements of voltage and current phasors in power grid. Students may use these data for parameters identifications of individual power components and for modeling and simulation study of a power grid. Online information and data of power grid

provided by EIA and RTOs/ISOs will help students to get big pictures from regional power grid operation to the whole North American electric grid. The new resources will provide students experimental experience with data collected from practical power grid instead of working with physical experimental systems in a laboratory. It will be significant to improve the undergraduate education program in power systems engineering and to attract students for cross-disciplinary education.

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