ELECTRIC POWER
RESEARCH INSTITUTE

UNIVERSITY GAPS ASSESSMENT IN DIGITAL POWER SYSTEMS EDUCATION

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Introduction

The Electric Power Research Institute (EPRI) and five Partner universities—University of California, Riverside (UCR), University of Texas, Austin (UT), Virginia Tech (VT), Stony Brook University (SBU), and Washington State University (WSU)—are collaborating on a DOE funded project called the Grid-Ready Energy Analytics Training with Data (GREAT with Data) initiative. The GREAT with Data initiative seeks to train and educate the next generation of the electric industry's workforce to address issues at the intersection of the physical power system and digital systems. The central theme is to create necessary training and educational (T&E) activities for the next generation of power engineers and data scientists, so they can design and develop the grid architecture and infrastructure to enable the integration of distributed energy resources (DER).

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As the transformation of the electric grid unfolds, developing a workforce trained in the range skills necessary to operate, enhance, and advance the planning and operations process is essential. The intersection of power systems and information systems technologies defines the new architecture for the electric system. The enabling strength of digital technologies will empower future electric system designers and operators the ability to accommodate a range options from distributed to central station assets. The new electric system expands the principle of the classic electric system from a traditional central station generation, transmission, and distribution system with static electric loads to a new order which embraces a grid architecture that includes load as an integral part of the electric system which is flexible and dispatchable, as well as integrates all DER as a fundamental part of the electric system.

The five Partner universities of the GREAT with Data initiative are leading the development of university curriculum to prepare the next generation power engineers and data scientists. These universities represent some of the top U.S. schools in the fields of electric power and information science that are necessary to form this electric grid architecture of the future. These five universities have worked together to develop a Gaps Assessment for the existing university power engineering curricula in three areas:

1. Data Analytics of electric power systems and the data provided through digital technologies
2. Information and Communications Technology (ICT) and Cyber Security
3. DER integration, specifically with regard to the integration achieved through deployment of digital technologies

The intent of this gaps analysis is to help inform the educational needs at universities to fill expected workforce development requirements in relevant fields in the electric power industry. Each of the three focus areas starts by describing desired competencies for the future workforce in the respective area which is a vital part of the overall gaps assessment process. The content of the competency framework for each area was established based on subject matter expertise, feedback from electric utility hiring managers, and other in-

Data Science				
School	UG	U/G	Grad	Total
SBU	1	–	4	**5**
UCR	2	1	1	**3**
UT	2	1	2	**5**
VT	2	–	4	**6**
WSU	–	–	1	**1**
Others	–	–	4	**4**
Total	**7**	**2**	**16**	**25**

ICT & Cyber Security				
School	UG	U/G	Grad	Total
SBU	1	–	5	**6**
UCR	1	–	6	**7**
UT	4	–	–	**4**
VT	3	–	6	**9**
WSU	2	1	2	**5**
Others		1	4	**5**
Total	**11**	**2**	**23**	**36**

DER Integration				
School	UG	U/G	Grad	Total
SBU	1	–	4	**5**
UCR	1	–	3	**5**
UT	3	1	1	**5**
VT	3	–	3	**6**
WSU	3	–	2	**5**
Others	2	5	9	**16**
Total	**14**	**6**	**22**	**42**

Figure 1. Summary of the number of courses included in the course inventory for each area of focus. (UG = undergraduate; Grad = graduate; U/G = cross listed course)

dustry resources. The competencies provided for each area of focus first define related topics of interest and then provide a succinct list of bullets on the high-level skills and knowledge students need when they graduate. The assessment that follows analyzes the gaps between these desired competencies and what current curricula offers in the specified area.

Course Inventory

Graduate and undergraduate courses offered at the five Partner universities of the GREAT with Data program are used as the basis for the gaps analysis. The project team has also reviewed relevant courses from other universities that are participating in EPRI's Grid-Ed program as an Affiliate University or courses that were developed as part of the DOE GEARED program. Further, courses were categorized into undergraduate, graduate, or cross-listed courses. In total, 84[1] courses were analyzed from 19 universities. A full list of the courses which were reviewed can be found in the Appendix.

Data Analytics for Power Systems with Digital Technologies

Electric utilities in the U.S. are stepping up the effort on developing applications of machine learning and big data analytics to improve the reliability, efficiency, and resiliency of power systems. Even during the COVID-19 pandemic, electric utilities are still actively recruiting data scientists, data analysts, and data engineers. For example, a Google search of data science/data analyst job for electric utilities on July 1, 2020 would reveal more than 100 positions in the U.S. Many electric utilities are accelerating the buildup of data science team. For example, the number of data scientists at Duke Energy increased from 6 to 41 in five years.[2] The fast increase in the number job positions and a lack of training and education material makes is difficult for electric utility companies to find qualified candidates with both data science skills and background knowledge in or the desire to learn modern power systems.

Competency Framework – Data Analytics

The following is a competency framework for someone who will be performing data analytics work in electric utilities. This applies to both a power engineer who is moving into data science area and a data analytics who is now performing analysis in the power engineering area.

Design Analysis

- Discover the needs for data analytics in electric power systems with digital technologies.
- Explicitly plan the data analysis in the power system domain.
- Anticipate and address competing explanations using data science and power engineering knowledge.
- Determine the best way to evaluate the data analytics results in the context of power system.

Conduct Analysis

- Explore the data appropriately.
- Build or apply appropriate algorithms with power engineering domain knowledge.
- Clearly summarize results and document findings.

1 Some courses were included in more than one of the three focus areas of study for this report.

2 https://www.sas.com/en_us/insights/articles/data-management/the-opportunity-of-smart-grid-analytics.html

	Power Systems	↔	Machine Learning and Data Mining		
	Classical Data Processing Techniques	Bridging Courses	Data Science	Machine Learning	Statistics
Undergrad	Power System Analysis		Data Science Laboratory Data Science Principles	ECE Machine Learning Artificial Intelligence and Engineering Applications CS Machine Learning	Nonparametric Technique
Under/Grad		Introduction to Power Distribution Systems Power Quality and Harmonics			
Graduate	Power System Operation and Control Computer Methods in Power Engineering	Big Data Analytics in Smart Grid Data Analytics in Power Systems Smart Energy in the Information Age Cyber-Power Systems	Big Data Analysis Big Data Systems, Algorithms, and Networks Big Data Analytics	Advanced Machine Learning Deep Learning Reinforcement Learning Theory and Practice	

Figure 2. GREAT with Data partner university courses in power systems and data science

Incorporate Analyses into Power System Planning and Operation

- Read/write data to/from power system applications.
- Integrate data analytics work into power system planning and operation processes.
- Package data analytics work for visualization and reporting.

Analyzed Curricula

Students seeking to contribute to the power industry as a data scientist or data engineer have the option of taking courses within of five topic areas as illustrated in Figure 2. These five topic areas were identified by analyzing courses at the five GREAT with Data Partner universities in power systems and data science. The left side of the figure shows power systems courses that use classical data processing techniques. The right side of the figure lists machine learning and data mining courses that are often offered by statistics and computer science departments. The bridging courses in the middle link the power system domain knowledge to machine learning techniques.

Undergraduate curriculum

The number of undergraduate courses offered by the five Partner universities in the area of data science for power systems is quite limited compared to the graduate level courses.

Virginia Tech (VT). The electrical and computer engineering department at VT offers two relevant undergraduate level courses: ECE 4424 Machine Learning and ECE 4524 Artificial Intelligence and Engineering Applications. These two courses cover the fundamentals of machine learning and ratification intelligence, and programing languages for artificial intelligence.

University of California, Riverside (UCR). The electrical and computer engineering department at UCR offers one relevant undergraduate level course (cross-listed): EE 253 Introduction to Power Distribution Systems. The second half of the course focus on applications of machine learning and big data analytics in power distribution systems. The statistic department offers one relevant undergraduate level course: STAT 140, which covers two applications of machine learning in power systems with noisy data.

University of Texas, Austin (UT Austin). The electrical and computer engineering department at UT Austin offers three relevant undergraduate courses: EE 460J Data Science Laboratory, EE461P Data Science Principles, and EE394 Power Quality and Harmonics (cross-listed). EE 461P covers algorithms of data mining and EE 460J covers applications in engineering domain. EE394 covers data analytics for various power quality disturbances.

Stony Brook University (SBU). The computer science and engineering department at SBU offers one relevant undergraduate course: CSE 353 Machine learning, which covers fundamental concepts for intelligent systems that autonomously learn to perform a task and improve with experience.

Washington State University (WSU). WSU does not offer undergraduate level course with a focus on machine learning and big data analytics in power systems and smart grids.

Graduate Curriculum

Thanks to high research interest in the area of data science for power systems, there exists a significant inventory of related options for graduate level courses offered by the five Partner universities.

Virginia Tech (VT). The electrical and computer engineering department at VT has two graduate courses, offered by the power area, that cover topics on data science: ECE 5314 Power System Operation and Control and ECE 6334 Computer Methods in Power Engineering. These two courses introduce relevant data processing techniques for classical power systems applications such as state estimation or optimal operations. In addition, there are two other graduate courses that aim to provide a comprehensive treatment of data science/machine learning: ECE 5424 Advanced Machine Learning and ECE 6524 Deep Learning. These two courses cover the fundamentals of machine learning and related advanced topics.

University of California, Riverside (UCR). The electrical and computer engineering department at UCR offers two relevant graduate level courses: EE 260 Big Data Analytics in Smart Grid and EE 253 Introduction to Power Distribution Systems (cross-listed). EE 260 is specifically designed to introduce key data analytics for power systems such as transmission systems, smart grids, and electricity market. As for EE 253, its second half focuses on applications of machine learning and big data analytics in power distribution systems.

University of Texas, Austin (UT Austin). The electrical and computer engineering department at UT Austin offers two relevant graduate courses: EE 394V Data Analytics in Power Systems and EE 394 Power Quality and Harmonics (cross-listed). EE 394V covers topics on data-enabled inference and learning techniques with their applications in power systems, while EE 394 covers data analytics for various power quality disturbances. The computer science department at UT offers one relevant graduate course: CS 394R Reinforcement Learning Theory and Practice, which covers algorithms and applications of reinforcement learning.

Stony Brook University (SBU). The applied mathematics and statistics department at SBU offers three relevant graduate level courses, including one that specializes on applications of machine learning in smart grid: AMS 559 Smart Energy in the Information Age. The other two courses that provide general overview of big data analysis and related advanced topics are: AMS 598 Big Data Analysis and AMS 560 Big Data Systems, Algorithms, and Networks. The computer science and engineering department at SBU offers one relevant graduate course: CSE 545 Big Data Analytics, which covers concepts and standard tools used to analyze big data.

Washington State University (WSU). The electrical engineering and computer science department at WSU offers one relevant graduate level course: EE 582 Cyber-Power Systems. It introduces data science topics such as anomaly detection and data analytics for cyber-power system.

Summary of Curriculum from Non-Partner Universities in Data Science Area

Four courses from non-Partner universities that cover topics in data analytics for power system were also reviewed. The first three courses only use classical data processing techniques while the last course can be considered a bridging course.

- **Missouri University of Science and Technology**. *EE5540 – Power System Engineering* covers the classical data processing technique for state estimation.
- **Clarkson University**. *EE553 – Power System Reliability* covers both basic probability theory of its application in analysis of interconnect system reliability.
- **University of Central Florida**. *EEL 5250 – Power System Detection and Estimation* covers the topics of static and dynamic state estimation with PMU data.
- **University of Central Florida**. *EEL 6257 – Data Analytics in Power Systems* covers the topic of feature engineering, reinforcement learning, and data-driven optimization.

Summary of Gaps and Conclusions

The current curriculum at the five Partner universities have provided a comprehensive list of concepts and topics in the area of data science in power systems. Quite a few courses have been specifically developed for introducing data science topics with an emphasis on power system applications. In addition, several universities have established the data science/machine learning courses for (electrical) engineering students in general. Nonetheless, the following two gaps in the existing curriculum prevail and hence, call for additional efforts in curriculum development for this area.

First, ***there is a lack of broad course offerings in data science for power systems applications at the undergraduate level***. Most of the existing courses are at the graduate level and thus may have missed the opportunity to prepare undergraduate students for this timely area. At the undergraduate level, the current curriculum has covered

some data science topics in a couple of power area courses (focusing on distribution systems or power quality, for example). While there exist several general data science courses, none are specifically developed for power systems applications. This gap means that an undergraduate student focusing on power/energy systems may have to take a course outside of one's own focus area to learn data science concepts, while taking additional effort to connect these concepts to power system applications. One potential solution is to cross-list several graduate-level courses to fill this gap but implementing this may depend on institutional policies.

Second, **there is little coordination among new courses on data science for power systems in the academic community**. Considering courses focusing on this area are relatively new, the list of topics and concepts that should be covered has not been widely discussed and vetted by the power engineering education community. There is an opportunity for the GREAT with Data initiative to help fill this gap by organizing such an effort.

ICT and Cyber Security

Traditional power systems programs provide a strong background in the physical power systems. However, as deployment of new technologies in ICT and cyber security increases in the power industry, it is increasingly important that both undergraduate and graduate students are provided with an adequate background in these new technology areas that are critical for power system planning, monitoring, operation, control, and protection. ICT is increasing at an unparalleled pace. It is estimated that 83% of enterprise workloads will be in the cloud by 2020 and 94% of enterprises already use a cloud service.[3] Cyber-attacks are no longer rare and have severe consequences.[4]

Competency Framework – ICT & Cyber Security

The following important areas of competency knowledge and skills were identified for someone who will be performing ICT and cyber security related work in electric utilities. This applies to both a power engineer who is moving into ICT and cyber security related areas and a systems manager who is now directing the ICT and cyber security activities for power systems.

3 https://hostingtribunal.com/blog/cloud-adoption-statistics/#gref
4 https://www.wired.com/story/power-grid-cyberattack-facebook-phone-numbers-security-news/

Information and communications technology with data acquisition

- Internet/proprietary networking in electricity markets/power system operations.
- Communications for power system operation, control, substation and distribution automation, Advanced Meeting Infrastructure (AMI).
- Communication protocols and standards for power grids.
- Advanced computing: graphics processing unit (GPU) and other accelerators, cloud computing, edge computing.

Cyber security and vulnerabilities

- Cyber security concepts and technologies for power grids.
- Vulnerabilities of cyber-attacks and intrusions in power grid components and systems.
- Critical Infrastructure Protection (CIP) standards.

Cyber-power system security

- Cyber security for inverters, Supervisory Control and Data Acquisition (SCADA), renewables, AMI, distribution automation, substation automation and microgrids.
- Independencies between cyber systems and power systems.
- Cyber-physical system security of an integrated cyber-power system.

Analyzed Curricula

As shown in Figure 3, courses are presented at undergraduate, undergraduate/graduate combined, and graduate levels. Regarding the topics, the traditional power courses are listed left most (dark blue), followed by courses leveraging ICT/cyber security in power systems (light blue). From the right most side, courses are mostly ICT and cyber security (green), followed by cyber-physical systems (dark green). In the middle are courses aiming at bridging the gap between physical systems and digital systems regarding ICT/cyber security.

Power Systems: Traditional power system curriculum in the senior undergraduate level normally has a core course on power system analysis, of which the main component is power flow modeling and computation. This is the fundamental subject for power system planning and operation. Power system control is primarily concerned with economic dispatch and automatic generation control.

	Power Systems		⟷	Machine Learning and Data Mining		
	Traditional Power	**Use Communications**	**Bridging Courses**	**Cyber Physical**	**Cyber Security**	**Computer Networking/ Science**
Undergrad	Power System Analysis	Smart Grids	Cyber-Infrastructure for the Smart Grid		Computer Security Fundamentals	Cloud Computing
					Network Security and Privacy	Intro to Computer Networks
	Power System Analysis and Control	Power System Protection	Electric Energy Distribution Systems		Information Security and Privacy	
Under/Grad			Distributed Control and Optimization for Smart Grids		Computer Security	
Graduate		Power System Operation and Control	Power Systems under Abnormal Operating Conditions	Cyber Physical Systems	Cybersecurity and IoT	Cloud Computing
		Power System Dynamics	Cyber-Power Systems		Networks and Protocols	Cloud Computing and Cloud Networking
		Big Data Analytics in the Smart Grid	Smart Energy in the Information Age		Network Security	Computer Communication Networks
		Modern Grid with Renewables	Microgrids		Computer Security	
			Introduction to Power Distribution Systems		Computer System Security	
			Power System Steady State and Market Analysis		Information Security	

Figure 3. GREAT with Data partner university courses in power systems and ICT & Cyber Security

The subject of communications is involved with the following courses including grid modernization (smart grid technologies), power system protection, power system operation and control, power system dynamics, and big data analytics in a modern grid.

ICT and Cyber Security: Computer networking is a general basic course in ICT. The related courses include introduction to computer networks, computer communication networks, cloud computing and cloud networking. As connectivity increases, cyber vulnerabilities also arise. Cyber security courses include fundamentals, network security and privacy; information security and privacy; computer security; cyber security and Internet of Things (IoT); networks and protocols; and computer system security. An emerging subject in the graduate curriculum is cyber-physical systems.

Bridging Courses: Bridging courses are those that integrate the subjects of power systems and ICT/Cyber security. Existing graduate and undergraduate courses include: cyber-infrastructure for the smart grid, cyber-power systems, and smart grid in the information age. Some courses are offered under traditional power systems titles; however, the subject of ICT/Cyber security is integrated as a module, e.g., electric energy distribution systems, power system steady-state and market analysis, microgrids, and power systems under abnormal operating conditions.

Example Bridging Courses

Virginia Tech ECE5984 Power Systems Under Abnormal Operating Conditions: The graduate level course starts with the traditional power system N-1 security concept and control center operational environment. To contrast the limited N-1 security scenarios that does not cause an outage, the course discusses catastrophic outages and cascading events. The weather-related vulnerabilities are extended to cover cyber vulnerabilities. Defense system methodologies include wide area protection and control as well as load shedding. Cyber intrusions are mitigated by intrusion detection algorithms. Modeling and simulation based on integrated cyber and power system models, leading to a platform for analysis of cyber-physical system security. Cyber security and mitigation methods are discussed for the areas of SCADA, substations, renewables, automation, and AMI. When the power system is in a blackout or a partial shutdown, decision support tools are used for power system restoration, including transmission and distribution systems. As the number of catastrophic outages increases, the need for a resilient distribution system is also gaining attention by government and industry. New concepts and computing methods for resiliency-oriented service restoration are included in this course.

Stony Brook AMS559 Smart Energy in Information Age: The graduate level course was recently developed and added to the Stony Brook University curriculum. It has been offered during the past three years for students in electrical and computing engineering,

applied mathematics and statistics, computer science, and other disciplines. The course covers the basics of cloud computing, edge computing, and their applications in power systems. Topics that are also discussed are machine learning and deep learning for energy predictions, joint data collection, energy prediction and control, economics for demand response, as well as online learning for energy provisioning. Four guest lectures are provided on cyber security and its applications in power systems, energy efficient computing, data science for power system operations, and learning for power system monitoring.

Summary of Gaps and Conclusions

This analysis is a starting point to identify the gaps between Power Systems and ICT-Cyber Security. Further analysis will need to involve more institutions and the industry. The objective of the gap analysis is to identify the courses/modules that will help to bridge the gaps. Based on present analysis, the following observations are made:

- ***There is a critical need for widely applicable outlines of bridging courses/modules.***
- ***Modeling of the cyber (information and communication) systems is lacking for power system applications.*** It is necessary to develop and modularize the cyber system models that can be interfaced with the large number of existing and future power system software tools.
- ***There is a great need to develop and incorporate an integrated cyber-power system security concept and methodology into curriculum.*** Existing power system analysis largely ignores the cyber systems and the interdependencies between cyber and power systems.
- ***Modeling software tools used in curricula lack the necessary characteristics of communications in power grids.*** Software tools such as NS-3 have been used for cyber network modeling; however, they are designed for computer networks and not customized for power grids.
- ***There is a critical need to closely integrate new technologies in power systems to enhance power system reliability, security and resiliency.*** New information and communication technologies are emerging, such as AI, decentralized operation and control, 5G, Internet of Energy, data centers, cloud computing, and edge computing.

DER Integration

The rapid integration of massive penetrations of DERs is one of the major challenges faced by the nation's power grid. While the variability and uncertainty of these generation resources challenge the existing notion of load-following power grid operations, the proliferation of power electronics raises significant concerns related to the stability and protection of the traditional power grid.[5] Digital technologies provide a promising prospect for managing the fast-changing phenomenon that the modern grid is subjected to by allowing for an even faster response to control and stabilize the grid.[6] As the deployment of the new digital technologies continues to grow in the power grid at both distribution and bulk grid levels, there is an increasing need to train both undergraduate and graduate students with an adequate background in these new technologies.

Competency Framework – DER Integration

To fully prepare our students for power grids of the future, we have identified the following important areas of competencies and the associated knowledge and skillsets that are needed:

- Alternative energy resources with the focus of energy conversion principles, modeling and analysis of variable generation technology, and their impacts on the traditional power grid.
- Grid integration of DERs with focus on power electronics interface and microgrid control and operations.
- Active power distribution systems with the emphasis on the integration of digital technologies to efficiently manage grid resources, demand response, and emerging retail electricity markets.

Alternative Energy Resources

- Alternative energy resources and power conversion technology – wind, solar, etc.
- Energy economics and sustainability.
- Modeling DERs and flexible loads – PVs, wind, battery storage, electric vehicles, HVAC, home water heaters, and cyclable loads like pool pumps.
- Impacts assessment of DERs in the power grid – power quality, voltage, stability, and protection related issues.

5 *IEEE Power and Energy Magazine*. "Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy." March–April 2017.
6 *IEEE Power and Energy Magazine*. "Grid-Forming Inverters: Are They the Key for High Renewable Penetration?" November–December 2019. https://ieeexplore.ieee.org/document/8879610.

Grid Integration of DERs – Power electronics interface and microgrids

- Power electronics interface to integrate DERs – inverter technology – grid-forming, grid-following, and grid-supporting technologies such as smart inverters.
- Modeling and simulation tools for microgrids with DERs.
- DER interconnection standards.

Active Electric Power Distribution Systems

- Simulation tools and modeling of active distribution systems.
- Emerging systems to manage DERs and microgrids – advanced distribution management systems, distributed energy resources management systems, and Microgrid energy management systems.
- Prosumers and demand-side participation – demand response, real-time pricing, home area networks, advanced metering systems, smart loads and appliances (buildings), and aggregators of DERs.
- Electricity market mechanisms for DERs in a distribution system – centralized or decentralized market, transactive energy, and ancillary services.

Analyzed Curricula

In this section, the relevant courses offered at the five Partner universities have been mapped into the identified areas of competency and knowledge related to DER integration. Next, based on this mapping of the courses and the analysis of the curriculum, the following summary of the strength and the gaps in the existing curriculum is provided in Figure 4.

Undergraduate Curriculum

Virginia Tech (VT). Offers three relevant undergraduate courses: EE 4224 (power electronics), EE 4364 (Alternate energy systems), EE 4984 (microgrids). The three undergraduate courses cover the fundamentals on power converter technology and power electronics for renewable resource integration, modeling and operation of microgrids along with different modes of microgrid operations (grid-forming/grid-following), fundamentals on the energy conversion process and delivery for alternate energy resources, and economics (long-term capacity credit and cost-benefit analysis). VT curriculum is extensive in capturing the power electronics interface for grid integration of DERs, microgrids, and energy conversion process for alternate energy systems.

University of California, Riverside (UCR). Offers two relevant undergraduate courses: EE 123 (power electronics) and EE 155 (power systems analysis). UCR undergraduate curriculum introduces basics on power electronics and inverter technology related to DERs. EE 123 includes topics on power electronics interface to integrated DERs. EE 155 introduces the concepts related to advanced metering infrastructure in power distribution systems.

	Alternative Energy Resources	Grid Integration of DERs	Active Electric Power Distribution Systems
Undergrad	Alternate Energy Systems Analysis of Power Systems with Renewable Energy Sources Introduction to Photovoltaics Renewable Energy Resource	Power Electronics Microgrids Power Electronics Laboratory	Power Systems Analysis Smart Grids Protection of Power Systems I
Under/Grad	Power Quality and Harmonics		
Graduate	Advanced Alternate Energy Systems Analysis of Power Systems with Renewable Energy Sources Modern Energy Technologies Introduction to Photovoltaics	Power Converter Modeling and Control Microgrids Systems Applications of Power Electronics	Power Systems Under Abnormal Operating Conditions Introduction to Power Distribution Systems Power System Steady State and Market Analysis Big Data Analytics in Smart Grid Smart Energy in the Information Age Power Quality Analysis

Figure 4. GREAT with Data partner university courses in power systems and DER Integration

University of Texas, Austin (UT Austin). Offers four relevant undergraduate courses: EE 494V (Analysis of Power Systems with Renewable Energy Sources), EE362G (Smart Grids), EE 462L (Power Electronics Laboratory), EE394/EE362Q (Power Quality and Harmonics); EE394/EE362Q is also cross-listed as a graduate course. Together these courses provide a comprehensive overview of modeling of DERs, including solar PVs, wind, energy storage, and electric vehicles; power conversion technology (power electronics interface); and the grid integration challenges of intermittent and variable renewable energy sources.

Stony Brook University (SBU). Offers one relevant undergraduate course: ESE 313 (Introduction to Photovoltaics). This course focuses on the analysis and modeling of solar energy resources, and the economic and environmental concerns of solar PV technology.

Washington State University (WSU). Offers three relevant undergraduate courses: EECS 492 (Renewable Energy Resource), EECS 486 (Power electronics), and EECS 493 (Protection of Power Systems I). Together, these course cover topics related to modeling of renewable energy generation technology including both solar and wind energy, power electronics for grid integration, and protection issues with DER integration.

Graduate Curriculum

Virginia Tech (VT). Offers three relevant graduate level courses: EE 5254 (Power Converter Modeling and Control), ECE 5374G (Advanced Alternate Energy Systems), and ECE 5984 (Power Systems under Abnormal Operating Conditions). EE 5254 builds on EE 4224 (power electronics) and focuses on the recent developments in power converter modeling and control (voltage mode and current mode control). ECE 5374G focuses on energy conversion from alternative energy sources and power system issues associated with the integration of small-scale energy sources into the electricity grid. ECE 5984 includes the relevant topic on using microgrid as a resiliency source utilizing distributed energy resources. VT graduate curriculum is extensive in capturing the power electronics interface for DER integration, microgrids, and energy conversion process for alternate energy systems.

University of California, Riverside (UCR). Offers three relevant courses: EE 253 (Introduction to Power Distribution Systems), EE 218 (Power System Steady State and Market Analysis), and EE 260 (Big Data Analytics in Smart Grid). Together these courses address the topics related to modeling and operation of active distribution systems. EE 253 includes topics related to modeling of DERs and flexibles loads and impact assessment of DERs on voltage and protection. EE 218 introduces distribution-level electricity market mechanisms for DERs. EE 260 includes advanced control and operational mechanisms for active distribution systems including Reinforcement Learning-based Control.

University of Texas, Austin (UT Austin). Offers three relevant graduate level courses: EE394/EE362Q (Power Quality and Harmonics, also cross-listed as undergrad course) and EE394V (Analysis of Power Systems with Renewable Energy Sources). The focus of graduate-level courses is on modelling and analysis of the integration of renewable energy sources, particularly photovoltaic (PV) and distributed energy storage (DES). Issues of interest include distribution systems impacts, associated power quality issues, grid impacts, and accommodation limits.

Stony Brook University (SBU). Offers four relevant graduate level courses: ESE 509 (Modern Energy Technologies), ESE 513 (Introduction to Photovoltaics), ESE 586 (Microgrids), and AMS 559 (Smart Energy in the Information Age). ESE 509 and ESE 513 focus on the modeling and analysis of alternate energy resources (wind, solar, geothermal, bio, ocean, hydro, etc.) along with grid-scale storage and their grid integration. EE 586 provides the background on microgrid modeling and analysis, including hierarchical control architecture. AMS 509 includes topics related to demand response and decision-making for prosumers. Overall, the graduate curriculum at SBU is extensive in modeling and grid integration of alternative energy resources.

Washington State University (WSU). Offers two graduate-level courses: EECS 582.01 (Power Quality Analysis) and EECS 525 (Systems Applications of Power Electronics). Together these courses include advanced topics related to both active distribution systems and microgrids. Related topics on active distribution systems include modeling, simulation, and impacts assessment of DERs; and, power electronic interface for grid integration of DERs. On microgrids, the graduate courses introduce topics related to microgrid modeling; control and operation; and power quality problems and mitigations in grid-connected and islanded microgrids.

Example Courses

VT ECE 4984 Microgrids

The undergraduate level course covers topics related to microgrid control modes and components. The course begins with the discussions on steady-state analysis and power quality, continuing to

topics related to control modes and hierarchy for the microgrid operations. Topics related to renewables resources and inverters, their protection strategies, and cyber security are also covered. Finally, the concept of DC microgrids and data centers is introduced. This course bridges the gap in the existing literature related to microgrids, DERs, inverter-based resources, control modes, and cyber security. Additional course modules are proposed related to PV technology, integration, and interfaces.

WSU EE 485 Electric Power Distribution Systems

This is a senior-level undergraduate course designed to teach the fundamental principles for distribution system engineering. The course objective is to provide each student with the ability to analyze, design, and operate distribution systems. The theory is supplemented by modern software tools for system planning and operation. The primary focus is on differentiating the distribution grid operations from the bulk grid by focusing on voltage regulation problems, the challenges with phase unbalance, and the reliability due to radial operational topology. The course introduces the need for phase-frame modeling and analysis as opposed to positive-sequence only analysis that students are familiar with from bulk grid modeling. A simulation project models a medium-size distribution system and performs power flow and voltage regulation analysis.

As of now, the course does not include the topics related to recent advances in distribution systems operations specific to the integration of digital technologies for active management of the resources. As a part of the GREAT with Data project, additional course modules will be developed to supplement the existing material with new topics highlighting the integration of digital technology. The course modules will include a discussion on the architecture for the advanced distribution management system and new distribution management applications leveraging control and communication technology with the emphasis on the digitization of the grid. Analysis, modeling, and demonstration of two basic applications for distribution grid will be included: Fault location, Isolation and Service Restoration (FLISR) and Volt-VAR Optimization.

Conclusions

Strength of the Existing Curriculum

- The undergrad curriculum at Partner universities has a strong emphasis on power conversion technology with regard to alternative energy resources (solar, wind, storage) and power electronics for renewable resource integration.
- The graduate curriculum typically includes advanced topics related to power electronics interface with various converter technologies, microgrid modeling, and control and impact assessment of DERs on electric distribution systems.
- Together the graduate and undergraduate curriculum is capable of building competency in modeling and analysis of alternative energy resources, technologies for their grid integration, and their impact assessment on the grid. The courses on topics related to the alternative energy resources and grid integration of DERs are well structured and taught with the same rigor as traditional power systems topics.

Identified Gaps in the Existing Curriculum

- There is a gap on courses related to ***active distribution systems and DER-interfaced microgrids with regard to the use of digital technologies***. While a few relevant topics are covered in some courses, there lacks a consistent framework to address this topic. Specifically, to build the competency in the area of active distribution systems and DER-interfaced microgrids, this topic needs to be introduced in the syllabus in a consistent manner. This can be achieved either by introducing new courses on the subject or by systematically introducing the related topics in the existing courses.
- ***Generally, the curriculum is limited in the topics related to active power distribution systems***. While certain elements of the relevant topics are included in the curriculum, it is not well structured. Further emphasis is needed on the changing distribution system paradigm with specific focus on emerging systems to manage DERs and microgrids, new operational technologies/approaches/architectures with smart inverter technology, prosumers/demand response, and emerging distribution-level markets.

- ***There is little content describing how energy storage and flexible loads can be used to mitigate impacts of intermittency caused by renewable energy***. This includes the technical requirements as well as emerging market and regulatory practices to address these future challenges.
- ***Existing content related to microgrids with DER technology needs revisions based on new research developments***. This includes adding new course materials on topics including emerging grid-forming/grid-supporting/grid-following modes of operation, interaction between synchronous generators and inverter-based resources with widely different time scales, new control architectures to manage DER-interfaced microgrids, and the use of DERs for enhancing grid resilience.

Summary

The content of this gaps assessment in digital power systems education focused on three broad technical areas which are envisaged as being crucial to the development of the modern electric grid. It first identifies the high-level skills and knowledge needed by the next generation of electric power engineers and data scientists for planning and operating the modern electric grid. Further, it assessed courses and course content from leading universities to identify a gaps in university curricula that can be addressed to provide a more robust educational experience to prepare the students for the needs of the future workforce.

Appendix

Table 1. List of courses analyzed in the area of Data Analytics of Power Systems and the Smart Grid

University	Course #	Title
Clarkson University	EE 553	Power System Reliability
Missouri University of Science and Technology	EE 5540	Power System Engineering
Stony Brook University	SBU598	Big Data Analytics
Stony Brook University	SBU545	Big Data Analytics
Stony Brook University	SBU560	Big Data Systems, Algorithms, and Networks
Stony Brook University	SBU353	CS Machine Learning
Stony Brook University	AMS559	Smart Energy in the Information Age
University of California, Riverside	EE 260	Big Data Analytics in Smart Grid
University of California, Riverside	EE 253	Introduction to Power Distribution Systems
University of California, Riverside	CS 140	Nonparametric Technique
University of California, Riverside	EE 155	Power System Analysis
University of Central Florida	EEL 6257	Data Analytics in Power Systems
University of Central Florida	EEL 5250	Power System Detection and Estimation
University of Texas, Austin	394V	Data Analytics in Power Systems
University of Texas, Austin	460J	Data Science Laboratory
University of Texas, Austin	461P	Data Science Principles
University of Texas, Austin	394/EE362Q	Power Quality and Harmonics
University of Texas, Austin	UT394R	Reinforcement Learning Theory and Practice
Virginia Tech	5424	Advanced Machine Learning
Virginia Tech	4524	Artificial Intelligence and Engineering Applications
Virginia Tech	6334	Computer Methods in Power Engineering
Virginia Tech	6524	Deep Learning
Virginia Tech	4424	ECE Machine Learning
Virginia Tech	ECE5314	Power System Operation and Control
Washington State University	EE582	Cyber-Power Systems

Table 2. List of courses analyzed in the area of ICT and Cyber Security

University	Course #	Title
Portland State University	ECE510	IoT for Grid Modernization II
Stony Brook University	CSE356	Cloud Computing
Stony Brook University	CSE331	Computer Security Fundamentals
Stony Brook University	CSE509	Computer System Security
Stony Brook University	ESE543	Cyber Physical Systems
Stony Brook University	ESE586	Microgrids
Stony Brook University	AMS559	Smart Energy in the Information Age
University of California, Riverside	EE 260	Big Data Analytics in Smart Grid
University of California, Riverside	CS 208	Cloud Computing and Cloud Networking
University of California, Riverside	CS 255	Computer Security
University of California, Riverside	EE 253	Introduction to Power Distribution Systems
University of California, Riverside	EE 155	Power System Analysis
University of California, Riverside	EE 249	Power System Dynamics
University of California, Riverside	EE 218	Power System Steady State and Market Analysis
University of Central Florida	EEL5291	Distributed Control and Optimization for Smart Grids
University of Memphis	EECE4205/6205	Modern Grid with Renewables
University of Pittsburgh	ECE/CoE 1188	Cyber-Physical Systems Laboratory
University of Pittsburgh	ECE1155	Information Security
University of Texas, Austin	CS378	Cloud Computing
University of Texas, Austin	EE379N	Information Security and Privacy
University of Texas, Austin	CS361S	Network Security and Privacy
University of Texas, Austin	EE362G	Smart Grids
Virginia Tech	ECE5434	Cyber-Physical Systems
Virginia Tech	ECE5480	Cybersecurity and the Internet of Things
Virginia Tech	ECE4984	Electric Energy Distribution Systems
Virginia Tech	ECE5584	Network Security
Virginia Tech	ECE5485	Networks and Protocols
Virginia Tech	ECE4334	Power System Analysis and Control
Virginia Tech	ECE5314	Power System Operation and Control
Virginia Tech	ECE4354	Power System Protection
Virginia Tech	ECE5984	Power Systems under Abnormal Operating Conditions
Washington State University	CptS/EE555	Computer Communication Networks
Washington State University	CPTS427/527	Computer Security
Washington State University	EE439	Cyber-infrastructure for the Smart Electric Grid
Washington State University	EE582	Cyber-Power Systems
Washington State University	CptS/EE455	Introduction to Computer Networks

Table 3. List of courses analyzed in the area of DER Integration

University	Course #	Title
Arizona State University	EEE472/591	Power Electronics and Power Management
Arizona State University	EEE598	Renewable Electric Energy Systems
Arizona State University	EEE572	Advanced Power Electronics
FAMU-FSU College of Engineering	EEL 5288/4930	Integration of Distributed Generation
Iowa State University	EE 459/559	Electromechanical wind energy conversion and grid integration
Missouri University of Science and Technology	EE 5001	Microgrid Systems and Architectures
Stony Brook University	313	Introduction to Photovoltaics
Stony Brook University	513	Introduction to Photovoltaics
Stony Brook University	ESE586	Microgrids
Stony Brook University	509	Modern Energy Technologies
Stony Brook University	AMS559	Smart Energy in the Information Age
The University of Memphis	EECE4205/6205	Modern Grid with Renewables
University of California, Riverside	EE 260	Big Data Analytics in Smart Grid
University of California, Riverside	EE 253	Introduction to Power Distribution Systems
University of California, Riverside	EE 123	Power Electronics
University of California, Riverside	EE 155	Power System Analysis
University of California, Riverside	EE 218	Power System Steady State and Market Analysis
University of Central Florida	EEL 5291	Distributed Control and Optimization for Smart Grids
University of Central Florida	EEL3290	Global Energy Issues
University of Central Florida	EEL 6253	Power System Resilience
University of Central Florida	EEL 6938	Special Topic: Power System Optimization
University of Hawaii	MW 696	Modern Electrical Grids and Electricity Markets for 100% Renewable Energy
University of North Carolina at Charlotte	ECGR 4090/5090	Utility Applications of Power Electronics
University of Pittsburgh	ECE 1710	Power Distribution Engineering and Smart Grids
University of Puerto Rico	INEL 6995	Distributed Energy Resources
University of South Carolina	ELCT 554	Integration of Photovoltaics in Modern Power Systems
University of Texas, Austin	394V	Analysis of Power Systems with Renewable Energy Sources
University of Texas, Austin	494V	Analysis of Power Systems with Renewable Energy Sources
University of Texas, Austin	462L	Power Electronics Laboratory
University of Texas, Austin	394/EE362Q	Power Quality and Harmonics
University of Texas, Austin	EE362G	Smart Grids
Virginia Tech	5374G	Advanced Alternate Energy Systems
Virginia Tech	4364	Alternate Energy Systems
Virginia Tech	ECE4984	Microgrids
Virginia Tech	ECE5254	Power Converter Modeling and Control
Virginia Tech	ECE4224	Power Electronics
Virginia Tech	ECE5984	Power Systems under Abnormal Operating Conditions
Washington State University	EE486	Power Electronics
Washington State University	EE582.01	Power Quality Analysis
Washington State University	EE493	Protection of Power Systems I
Washington State University	EE492	Renewable Energy Resources
Washington State University	EE525	Systems Applications of Power Electronics

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