Towards Designing and Developing Curriculum for the Challenges of the Smart Grid Education

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Abstract—**At the tipping of a paradigm shift in the way energy is produced, transmitted and delivered, the research efforts have not been paralleled by the curricular development. With rapid pace of changes in the field of Smart Grid (SG), the traditional research and educational efforts have been a major domain for electrical engineers. As a mode of discovery and education, interdisciplinarity facilitates broadened perspectives, ability to synthesize, analyze, integrate, and apply knowledge, and out-of-the-box thinking. The major contributions of this paper are discussion of requirements of the educational efforts in SG with special emphasis on multidisciplinarity, survey of the related work, which is the first in the literature to the best of our knowledge, and a discussion of the content for such an effort. A mixed team of power engineers and computer scientists are developing a layered curriculum starting from the introductory material from a variety of SG topics. A distinguishing advantage is the availability of many software tools and the state-of-the-art testbed as a result of years of research.**

I. Introduction

Under an aging and increasingly ineffectual energy delivery systems, unprecedented initiatives have recently been instituted around the world to ameliorate the electric grid with the Smart Grid (SG). The key facilitators of the new SG are the bidirectional energy and information flow between the suppliers and consumers, which necessitate integration of information and communications technologies. The research and educational initiatives have been mostly disciplinary. However, the changing field, especially under the light of its increasingly complex problem sets, the unidirectional effort does not seem to be sufficient any more. Multidisciplinarity appears to be a strong candidate for the curriculum development efforts. It is generally agreed, as pointed by the National Academy of Sciences report [1], that Interdisciplinary Research, Teaching, and Learning (IRTL), as a mode of discovery and education, facilitates broadened perspectives, ability to synthesize, analyze, integrate, and apply knowledge, more creative, original, and out-of-the-box thinking among other benefits. Many theories of learning, such as constructivism and situated learning, corroborate these benefits.

The goal of this paper is to facilitate curriculum development for SG education. Our contributions in this paper are as follows: (1) The requirements from the industry and academia are articulated, (2) A comprehensive survey of the related work and course offerings, (3) A synopsis of our own roadmap.

Many challenges and roadblocks do exist. Problem formulations, methodologies, accumulated repertoire of disciplinary culture, and knowledge gaps are some of the difficulties to arise. At this tipping of a paradigm shift in the way energy is produced, transmitted and delivered, the research efforts have not been paralleled by the curricular development. A mixed team of power engineers and computer scientists are developing a layered curriculum starting from the introductory material from power systems, protection, energy conversion and distributed generation, control systems, communications, renewables, electric vehicles, energy storage, cybersecurity, demand response, power system sensors. A distinguishing advantage is the availability of many software tools and the state-of-the-art testbed at TCIPG as a result of years of research in this new field. Hands-on exercises are to be complemented with interdisciplinary case studies to blend power, computing, communications and security perspectives. While there are some efforts in the literature and academe, to the best of our knowledge, there appears to be a need to have an inherently interdisciplinary textbook with a balanced approach on the disciplinary fundamentals that can used as an introductory material with end-of-chapter exercises. The books published on smart grid requires a significant effort by the instructors for use in the class. It is our belief that our effort is set to fill a gap in this area as the education of the workforce have become a priority with increasing demand for qualified graduates. Further, in the paper, we provide a taxonomy and discussion of the educational efforts related the SG. Finally, the core of this of paper is to serve as the stimulus of the curriculum for academic coursework to train the next generation of the engineers and researchers. We are in the process of the using the content of this paper as a seed to pave the way for developing a textbook, which is missing and highly needed.

The rest of this paper is organized as follows: Section IV delves into the pedagogical and theoretical underpinnings of co-op education. A taxonomy of co-op education programs as implemented by universities across the globe is presented in Section III together with the related work. Concluding remarks and synopsis of future work are given in Section VII.

II. Background

A. Smart Grid

Economic development and its sustainability are closely coupled with the effective, efficient and robust use of the energy. Under an aging and ineffectual energy distribution system, unprecedented initiatives have recently been instituted in many countries to ameliorate the electric grid with the Smart

Grid. Global investments on SG has exceeded $15 billion as of 2013, more than a four-fold increase from 2008 levels [2].

The key facilitators of the Smart Grid are two-way energy and information flow between the suppliers and consumers. The conventional supply-chain of the energy is being expanded to include alternative sources of energy, such as solar, wind, tidal, biomass, etc. from a variety of distributed small and large energy producers. The consumers are becoming more active participants by means of such devices as smart meters, smart thermostats, and smart appliances. The grand vision of autonomic, self-healing Smart Grid with a dynamic demand response model along with pricing still has many challenges, not the very least, from the perspective of the networking infrastructure and distributed computing. The sheer size of the contemplated Smart Grid of the future is to rival the Internet in the number of participants.

Smart Grid (SG) is a term generally used to refer to an enhancement of the traditional power grid, especially, in terms of the computing and communications technologies. The conception of the Smart Grid (SG) paradigm is to offer many benefits to the transmission, distribution, and consumption of energy. The existing power grid is currently used to carry power from a few central generators to a vast number of consumers through a transmission and distribution network. On the other hand, SG uses two-way flows of electricity and information to create an automated, secure, and distributed advanced energy delivery network. Smarter generation, transmission, distribution and consumption of electricity is essential to achieve a reliable, clean, safe, resilient, secure, efficient, and sustainable power system [3].

Some of the noteworthy standardization efforts, high-level conceptual reference models and roadmaps for SG are given by NIST Framework and Roadmap for Smart Grid Interoperability Standards [4], IEC Smart Grid Standardization Roadmap [5], CEN/CENELEC/ETSI Joint Working Group on Standards for Smart Grids [6], and IEEE P2030 [7]. A conceptual view

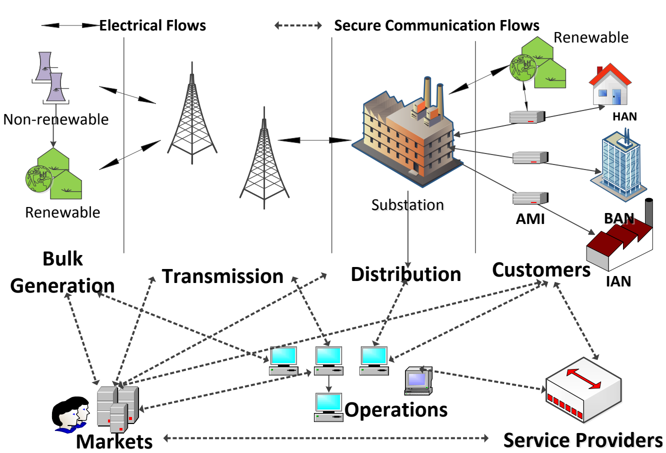

Fig. 1. NIST's Smart Grid Conceptual Model.

of the NIST's SG reference model is depicted in Figure 1. Note the bidirectional electric and information flow and the integration of the renewables.

B. Trustworthy Cyber Infrastructure for the Power Grid (TCIPG)

Researchers from the University of Illinois at Urbana-Champaign, Dartmouth College, the University of California at Davis, and Washington State University are together addressing the challenge of how to protect the nation's power grid by significantly improving the way the power grid infrastructure is built, making it more secure, reliable, and safe. This Department of Energy-funded project, with support from the Department of Homeland Security, recognizes that today's quality of life depends on the continuous functioning of the nation's electric power infrastructure, which in turn depends on the health of an underlying computing and communication network infrastructure that is at serious risk from both malicious cyber attacks and accidental failures. These risks may come from cyber hackers who gain access to control networks or create denial of service attacks on the networks themselves, or from accidental causes, such as natural disasters or operator errors.

TCIPG is addressing trust issues in the next-generation power grid cyber infrastructure, and has developed a large-scale cyber-physical testbed to facilitate that research. A well-established cyber-physical testbed facility not only enables Information Trust Institute (ITI) of the University of Illinois research, but also provides a proving ground that validates technologies before commercialization. The main purpose of the testbed facility is to serve as a realistic, flexible, configurable, and easily customizable environment that enables innovative research in end-to-end trustworthy power system communications and control. The facility uses a mixture of commercial power system equipment and software, hardware and software simulation, and emulation to create a realistic representation of the power grid. That representation can be used to experiment with next-generation technologies that span communications from generation through consumption and everywhere in between. In addition to offering a realistic environment, the testbed facility is instrumented with the latest research and commercial tools to explore problems from multiple dimensions, so that researchers can tackle in-depth security analysis and testing, visualization and data mining, and federated resources, and develop novel techniques for integrating these systems in a composable way.

C. Why Curriculum development in SG?

It is well-accepted that the US lags behind in math and science literacy rates among the 34 member countries in the OECD (Organization for Economic Co-operation and Development) as corroborated by the Science and Engineering Indicators of the National Science Board findings. A report by The 2012 Presidents Council of Advisors on Science and Technology (PCAST) [8] states that approximately 1 million more Science, Technology, Engineering, and Mathematics (STEM) graduates than expected are needed under the current assumptions.

SG is an emerging subfield within the STEM domain, experiencing huge investments worldwide with fast job growth

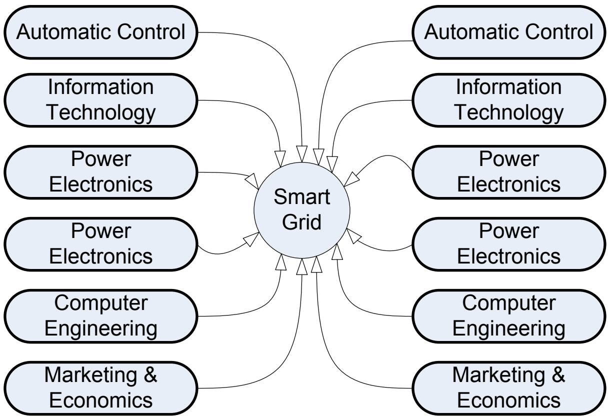

Fig. 2. Components of an integrative approach to smart grid design and operation from [30].

prospects. Shortage of engineering students, and faculty, is noted in [9]. Further, retooling of the existing workforce is needed as the jobs in the field now require a different set of skills than has been in the past [10].

III. Related Work

There are many efforts to bring up the SG-related education up to speed with the developments in the field. However, many are from power engineering curricula and confined to a disciplinary approach without passing beyond the boundaries, such as [11], [12], [13], [9], [14], [15], [16]. Some SG desired topics are recommended in [17], [18] and curriculum model [19] and curriculum need [20]. A laboratory displaying SG metering, protection, control, monitoring and communication has been developed at UAEU (United Arab Emirates University) [21]. A hardware-based laboratory smart grid test-bed at Florida International University is reported in [22] with Wide area monitoring (WAM), wide area protection (WAP), and wide area control (WAC) systems [23] and microgrid [24]. A distribution system laboratory, The Future Renewable Electric Energy Delivery and Management System, built at North Carolina State University is presented in [25], [26]. Elaboration for developing educational material for SG workforce need is provided in [10], [27], [28]. Some high level description of a crossdisciplinary graduate course, including material from communications, networking, control,and power systems is given in [29]. Another multidisciplinary approach for future power engineering education with an integrative approach is given in [30], see Figure 2.

There are a few books about SG, such as [31], [32], [33], [34], [18], [35]. Yet, none are readily usable in the classroom for university education. Most are not multidisciplinary.

IV. Pedagogical Framework

The traditional view of the fields of studies is usually termed as *disciplinarity* which is used to describe academic disciplines as autonomous and discrete areas with no or minimal cooperation over disciplinary boundaries [36], [37]. Since the seminal report by Organization for Economic Cooperation

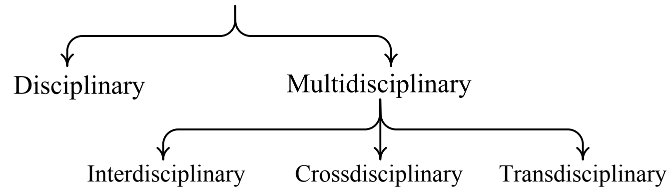

Fig. 3. Taxonomy of disciplinary approaches to fields of study.

and Development (OECD) on ”Interdisciplinarity: Problems of Teaching and Research in Universities” in 1972, there have been other approaches in the area of teaching and learning. Figure 3 shows a high-level taxonomy of these methods. Multidisciplinarity is an umbrella term to indicate a level of interactivity, cooperation or co-existence of a number of disciplines [38], [36]. It is generally agreed in the literature that there are three major categories of multidisciplinarity. *Crossdisciplinarity* is term to use when one discipline takes on topics normally outside of its own domain with no coordination or cooperation from the other field. When a field of study employs methodologies from other disciplines to attempt to solve the traditional problems of its own domain, the term *interdisciplinarity*[1] becomes the term to use. *Transdisciplinarity* refers to a higher level of cooperation and coordination among the participating fields of study where the boundaries are almost ignored to attack challenges to bring solutions using existing or new approaches. Table I compares and contrasts these terms with respect to the source of problems they study

	Challenges	**Methodology**
Disciplinary	Own	Own
Crossdisciplinary	Others	Own
Interdisciplinary	Own	Others
transdisciplinary	Own & Others	Own & Others

TABLE I
Comparison of disciplinary approaches with respect to problems they study and methodology they employ.

and the methodology they use in attempting to solve them.

Disciplinary-based studies provide the prerequisite toolbox for analyzing the world in a certain, systematic way. In more technical terms, they provide cognitive maps, frameworks and paradigms [40]. There are many benefits cited by the advocates of multidisciplinarity [41], [42], [43], including critical thinking, meta-cognitive reflection, problem-solving and analysis, self-direction, synthetic and other higher-order thinking, such integrative, creative, original, and unconventional. Existence of intricate and complex set of problems usually provide an initial justification for multidisciplinary approaches in research, teaching and learning [44]. A comprehensive report by a National Academies of Science Committee on Facilitating Interdisciplinarity [1] recognized multidisciplinarity as a val-

[1]While there are different definitions in the literature, we prefer this definition in part to clarify the delineation of scope of these closely related terms. Refer to [39], [38], [36] for more in depth discussions.

idated *mode of discovery and education*, and recommended that educators facilitate multidisciplinarity educational and training opportunities for undergraduates, graduate students, and postdoctoral scholars.

The topics that fall under the SG area encompasses a variety of fields of study, such as power engineering, electrical engineering, computer science, cybersecurity, cryptography, etc. and many of their subfields, roles, occupations, and sectors. For example, the cybersecurity alone is noted by the National Research Council very recent report [45] to require a broader approach that a single discipline may provide. SG area has many pressing complex problems and workplace expectations and needs. The fast pace contributing changes in the information, communications, and computing technologies pave the way for ore suitable and conducive environment for multidisciplinarity. We thus choose a transdisciplinary approach in our curriculum development. We expect a more coherent and connected learning and curriculum can result in. More efficient use of resources by avoiding duplications would be another benefit.

Many learning theories [43] corroborate the aforementioned benefits of multidisciplinary approaches in any field of study in general, and in SG-related topics in specific. It is generally agreed that cognitive theories from Educational Psychology [2] that when a learner is able to tap into his previous knowledge the learning process becomes more effective [46]. Multidisciplinarity, in this sense, is much more likely to invoke the cognitive map from disciplinary studies on the problems from many other fields to facilitate a more productive learning. Similarly, constructivist learning theory states that how learners construct their learning based on their past experience. Situated Learning Theories [47] suggest that complex, real-world problems, as often the case with SG-related topics, may serve as effective catalyzers to enhance learning because students are more readily engaged in authentic tasks similar to what they would be facing outside of the classroom and in work settings.

V. Courses

The following web site includes links to numerous educational material that has been developed under the ARRA program by the US Department of Energy:

https://www.sgiclearinghouse.org/Education

The following course trials have been created to include portions of both cyber and physical topics in one course.

A. Washington State U.

WSU Course Description: Introduction to smart electric grid, communication networks, distributed computing, fault tolerant computing, cyber security, analyzing interdependencies between the smart grid components, smart grid standards and protocols.

Goals: To introduce students to The fundamental principles of smart grid operation and control; Smart grid technologies including sensors, communication networks, computation, data management and cyber security; The interdisciplinary nature of the smart grid and the interdependencies between the component technologies on which its security depends

Course topics: Smart Electric Grid Overview (3 weeks) Communication (3 weeks) Power System Data Management and Computation (3 weeks) Cyber security (3 weeks) Linking all topics together (2 weeks)

Additional information may be obtained by contacting the instructors at:

Dr. Anurag Srivastava, E-mail: asrivast@eecs.wsu.edu, Phone: 509-335-2348. Office: EME 31, Dr. Carl Hauser, Email: hauser@eecs.wsu.edu, Phone: 509-335-6470, Office: EME 53, Dr. David Bakken, Email: bakken@wsu.edu, Phone: 509-335-2399, Office: EME 55

B. West Virginia U.

WVU Course description: Study of Cyber-Physical Systems (CPS), defined as cyber (computing/communication) systems that are embedded in the physical world and interact with it; examining design and modeling concepts, communication networks, and sensing and control architectures for cyber-physical systems such as intelligent transportation networks, smart grid, and industrial control systems; an overview of system modeling techniques from hybrid systems to stochastic modeling, application of wireless networks, control theory, and embedded system design concepts in emerging connected vehicles or smart grid.

Textbook: Lee and Seshia, Introduction to Embedded Systems: A Cyber-Physical Systems Approach, http://leeseshia.org/

Additional information may be obtained by contacting the instructors at:

Dr. Yaser Fallah, Room 831 Engineering Sciences Bldg, West Virginia University, Yaser.Fallah@mail.wvu.edu

C. Case Western Reserve U.

Case Western Course Description: Electric power system infrastructure and American national electricity policy; electrical power system operations; power system reliability; electricity market design and operation; Smart Grid technologies distributed generation, demand response resources, Advanced Meter Infrastructure; interconnection; interoperability standards; Smart Grid impact on power system reliability and electricity market design.

Topics by week: Overview of the power system infrastructure and review of US national electricity policy. Transmission system operation (1) Resource commitment. Transmission system operation (2) Generation dispatch. Transmission system operation (3) Real time operation. Electricity market (1) The Day-Ahead Market. Electricity market (2) The Real-Time Market. Electric distribution systems. Overview of the Smart Grid initiatives including Advanced Meter Infrastructure. Reviewable generation technologies. Demand response resources. Distributed generation and Microgrids. Stored energy technologies. Interoperability standards. Impact of Smart

[2] *Cognition* is term used by psychologists to refer to how people actually acquire knowledge.

Grid technologies on power system reliability and market design.

Additional information may be obtained by contacting the instructors at:

Professor Mingguo Hong, Case Western Reserve University, mxh543@case.edu

D. Oregon State U.

Oregon State Course description: Fundamentals of smart power grids. Technology advances in transmission and distribution systems. Policy drivers. Assets and demand management. Smart grid security.

Topics: Introduction to smart power grids. Technology and policy background. Smart generation. Energy storage. Micro-grids. Substation intelligence. Transmission systems. Phasor measurement units. Distribution systems. Smart grid monitoring and communications. Asset management. Consumer demand management. Smart meters and advanced metering infrastructure. High performance computing applications for smart grid. Smart grid security.

Additional information may be obtained by contacting the instructors at:

Professor Educardo Cotilla-Sanchez, Oregon State University, ecs@eecs.oregonstate.edu

E. U. of Illinois at Urbana-Champaign

M. A. Pai Course description: The course would be modular with the following topics:

Basics of Power system analysis with a computational flavor: P.S components, Network representation, load flow ,OPF and stability Computer Simulations of grid & Distribution Network using Commercial S/W

Communication Systems and networks: Communication networks, SCADA, Energy Management System (EMS), substation automation, sensors and actuators including relay and PMU technologies. Wireless, Power Line Carrier Last Mile Networking, Communication network simulation to understand impact of different topologies and deployments.

Elements of Smart grid: Automatic Billing, AMI, Energy efficiency, demand response, RES integration, interoperability, Reduction of ATC losses, Impact of EV.

Wide Area Measurement system and impact on security, Situational Awareness of the Grid

Cyber Security: Introduction to cyber security concepts, cyberphysical security, cyber attackdefense techniques and tools, cyber security standards and best practices.

Term project on cyber security or smart grid technologies.

Additional information may be obtained by contacting the instructors at:

M. A. Pai, mapai@illinois.edu

F. SUNY Binghamton

SUNY Binghamton Course Description: This course focuses the use of sensor networks and embedded computing devices for monitoring, modeling, controlling and reducing the carbon footprint of physical infrastructure such as buildings and electrical vehicles. It will also cover related topics such as green energy, e.g., solar and wind, and smart-grids, and their use in the computing and networking context.

Additional information may be obtained by contacting the instructor at:

Ting Zhu, Department of CS, State University of NY, Binghamton, zhuting2@gmail.com, tzhu@binghamton.edu

G. Carnegie Mellon U.

CMU Course description: Building a sustainable energy ecosystem, and controlling a complex electrical grid to provide this energy, poses one of the largest challenges facing the world. Although energy topics span many disciplines, ranging from power systems to public policy, it is becoming apparent that computational techniques such as simulation, prediction, optimization, and control have the potential to drastically impact virtually all of these areas. This course provides an introduction to recent advances in computational methods applied to sustainable energy and the smart grid; the goal is to provide students with a broad background in state-of-the-art computational methods that repeatedly arise in these domains, such as machine learning, optimization, and control, and to provide hands-on experience applying these methods to real-world domains. In particular, much of the class will use real data from the Pennsylvania electrical grid as a running example, and address issues regarding the prediction, modeling, and control of electricity from existing and renewable energy sources. Although listed in Computer Science, the course is expected to be of interest to students in many departments, including ECE, MechE, CEE, and EPP.

Application areas include electricity demand and renewable resource prediction, modeling energy consumption in buildings, electrical power systems, power flow, and power markets, control of distributed storage. Computational techniques include regression and classification, time series prediction, Newtons method for non-linear equations, convex optimization, and model predictive control.

Additional information may be obtained by contacting the instructor at:

http://www.cs.cmu.edu/ zkolter/course/15-884/

Zico Kolter, Carnegie-Mellon University, zkolter@cs.cmu.edu

H. U. of Central Florida

UCF Course description: Electric power systems, transmission and distribution networks, distributed generation and smart grid components, voltage stability and VAR control, dispatch of distributed generation, distributed optimization for loss minimization, frequency control, electricity markets and incentive controls

Additional information may be obtained by contacting the instructor at:

Dr. Zhihua Qu, University of Central Florida, qu@eecs.ucf.edu

I. Wichita State U.

Wichita State Course description: According the US Department of Energy Smart grid generally refers to a class of technology people are using to bring utility electricity delivery into 21st century using computer based remote control and automation. This initiative not only requires the power engineers to have a better understanding of the auxiliary fields like information technology, communication networks, control theory, and economics, but also needs experts in the auxiliary fields in order to understand the basic operations of power systems. This inter-disciplinary class will focus on various aspects of information-sharing at the consumer-level of smart grids such as power analysis, efficient communication and delivery systems, secure communication infrastructure, privacy enhancing technologies. A team of instructors will add perspectives of various disciplines and research areas to broaden student learning in smart grids through a cutting-edge, blended-learning format.

Topics: Introduction to Smart Grids; Introduction to Power Systems (Transmission, Generation, Distribution); Role of Information and Communication Technologies (ICT) in Smart Grids; How Economics of Supply and Demand, Information Security and Privacy, and Control System Theory fit into Smart Grids; Environmental considerations in Smart Grids; Topics of current research and application areas in Smart Grids

Additional information may be obtained by contacting the instructors at:

Vinod Namboodiri, Visvakumar Aravinthan, both at Wichita State University, Vinod.Namboodiri@wichita.edu, Visvakumar.aravinthan@wichita.edu

VI. Synopsis

Engineers that will design and work on the smart grid of the future will encounter extensive networks of communication, computing and cyber infrastructure in addition to traditional electric power equipment and associated controls. The education of these engineers should evolve to expose them to this vast new set of technology and processes. The concept of protection now includes cyber assets in addition to traditional physical power system assets. Servers that facilitate SCADA system infrastructures have a profound importance to ensure continuous and reliable electrical service. It is not an exaggeration to say that all of the topics of Electrical and Computer Engineering now touch the critical infrastructure equipment that ensures reliable electric power services. At the December, 2013 NSF National workshop on Energy Cyber-Physical Systems, the following content was proposed as being critical to any sequence of courses that seeks to prepare engineers for work on the smart grid of the future.

- Cyber-Physical-Systems include a complex interaction between traditional physics-based
- Fundamental laws of circuits and power systems
- Fundamental principles of power system sensors and protection
- Fundamental laws of energy conversion and distributed generation
- Fundamental concepts of control systems
- Fundamental concepts of communication devices
- Fundamental concepts of communication networks/wireless
- Fundamental concepts of computing devices
- Fundamental concepts of computer networks/routers/firewalls
- Basic principles of renewables hydro/solar/wind
- Basic principles of hybrid electric vehicles
- Basic principles of reliability plus generation and transmission capacity
- Basic principles of energy storage and efficiency
- Basic principles of cyber security
- Basic principles of demand response and market mechanisms
- Basic power system sensors, metering, control, SCADA, operations

In the past five to ten years, several universities have attempted to provide new courses within Electrical and Computer Engineering to prepare both electrical and computer engineers in the technologies that have emerged as important in smart grid infrastructures. These attempts have had variable success and seem to highlight the challenge of cross training young and old engineers in this expanding multidisciplinary field. This paper discusses some of these attempts and provides a summary of the needs that have emerged in our curricula. One outcome that has been reported in several attempts to educate both electrical and computer engineers in the same class involves the variation of previous courses that each has taken. The electrical engineers have taken courses in electrical networks and perhaps only very basic computer concepts. The computer engineers have taken courses in computer and communication networks and perhaps only very basic electrical power concepts.

VII. Conclusion

The Smart Grid (SG) is fast transforming itself to be a high in-demand field not only in research but also in teaching and learning. While the research efforts have picked up pace recently, the educational activities unfortunately have lagged behind. Students, industry, workforce and faculty are in need of educational material and curricula about the SG. In this position paper, we have discussed the emerging need in details for the curricula and presented an overview of a comprehensive related work from the published literature as well as from university course offerings. We have also included a synopsis of our own effort for designing and developing SG curricula. We hope that this paper will be useful for anyone who would like to develop SG-related educational material by using the content here as a starting point.

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