Integration, Innovation and Expansion in Energy Systems Education

Marija Ilic and Ed Schlesinger, Carnegie Mellon University

Introduction:

We are very pleased to have our feature article by Prof. Marija Ilic and Prof. and Head Ed Schlesinger, both in the ECE Department at Carnegie Mellon University. Prof. Ilic is a distinguished researcher and educator currently working in electrical energy systems. At this year's ECEDHA meeting she gave a talk on energy systems in a breakout session on undergraduate curriculum issues. Prof. Schlesinger is currently on the ECEDHA board of directors as vice president. Their article is quite timely, discussing electrical energy systems education and the programs that Carnegie Mellon University has implemented.

Abstract:

In this article we briefly comment on the state of current electric energy systems programs. We argue that for an educational program to have an impact an understanding of the challenges facing the electric energy industry is required. We explain how the industry has changed in major ways and describe the implications of these changes to new educational objectives. We also illustrate how these changes are being met through curricular implementation at Carnegie Mellon University.

1. State of Current Electric Energy Programs

A convergence of circumstances has put electric energy systems back at center stage for many researchers, universities, and students of electrical and computer engineering. These circumstances include 1) the broad realization that the electric energy system in the United States is brittle and subject to serious problems if it is not upgraded and modernized and 2) the growing interest in and need for the integration of new energy sources including renewable sources with traditional sources of energy. Renewable sources especially represent a technological challenge given their temporally and geographically intermittent nature. Added to these two circumstances is the technological potential of those technologies broadly categorized within Cyber Physical Systems that could make possible the upgrading of the electrical energy system; the control and monitoring of that system for greater efficiency, reliability and security.

Many universities, however, are finding themselves somewhat unprepared in the midst of this revived importance of and interest in energy and environment. In particular, they are facing an unprecedented challenge to introduce into what is typically an over-crowded ECE curriculum theoretical fundamentals and applications of electric energy systems that have impact in this changing industry. The sometimes reluctant recognition that something must be done must be reconciled with the belief that one must teach only general principles. Once the students graduate, so the thinking goes, they will learn the domain applications as part of their job. Many strongly believe that by the time students are taught how to think and become problem solvers, we have done enough to prepare them for all real-world challenges.

We believe that teaching fundamentals in a system context within an application domain is much more effective in general and in this particular area of energy and environment specifically. Introducing concepts of the general ECE discipline using the energy and environment area is a challenge and the bridge between the concepts which have historically evolved in the power industry, on the one hand, and basic ECE courses has been weak. Consequently, it is almost impossible to expect students who have not taken any power engineering courses to become forward-looking leaders or even to enter the market as members of a qualified new workforce. Typical students coming out of most ECE curricula today will have a difficult time understanding even the low-hanging fruits to be found through even modest innovation let alone become leaders to effect the transformation needed in the electric energy industry. On the other hand, students who have specialized in traditional power engineering often lack the ability to re-think the industry problems. Most ECE departments offer at most one or two electives in the power engineering area and many courses that are offered may not include topics relevant to the new technologies that need to be brought to bear in electric power systems today. In short, there exists an educational void, and there is some urgency to innovate and integrate electric energy systems education, into existing curricula.

In what follows we suggest that educating the next generation work force must be in the context of, and centered in, Electrical and Computer Engineering while also integrating concepts in ECE from other academic disciplines, including non-"technical" disciplines such as policy and economics. It is critical to recognize the key role of ECE in the emerging energy and environment curricula. In what follows we describe how key ECE disciplines are essential to the success of future energy systems.

2. State of the Electric Energy Industry

The electric power system is an old infrastructure, which has mushroomed over the past two centuries as electricity demand has grown. The electric power grid has become a rather complex electric network whose voltage levels range from very Extreme High Voltage (EHV) to the 110V in households. Power plants of various types and a wide variety of loads are connected between ground and the nodes of this network. At the terminals of the power grid many forms of energy conversion take place.

Utilities schedule their own power plants in a stationary feed-forward manner to meet forecast demand and exchange power with neighboring utilities. Only power imbalances due to deviations from forecasts are compensated by automatic generation control (AGC), which is a very simple but powerful feedback control responsible for balancing each utility to maintain high quality frequency. During abnormal conditions any automated process is disabled, except for protection relays which are dedicated to preventing equipment damage. System operators have pre-defined worst-case plans for managing failures of large equipment. At the same time it is almost impossible to predict worst-case scenarios in a complex network of this magnitude, and, consequently customers experience infamous blackouts. While it is impressive how well the system functions most of the time, given the overall level of complexity it is not something that can be taken for granted. A closer look into operations and planning principles reveals the assumptions which ensure such reliable performance; the cost is under-utilization during normal conditions. To prevent blackouts and to increase short-term utilization, it is necessary to rely more actively on on-line monitoring, faster control and computationally efficient and robust algorithms to enable timely decisions as system conditions change. Moreover, since the infrastructure is aging, much of the hardware infrastructure must be re-built and this requires engineering and policy knowledge to decide what is the right way to deploy these systems. At the same time the introduction of two way communications within the electric energy system immediately also requires the introduction of sophisticated network and software security systems to ensure the reliability and the resilience of this network against attacks and other forms of potential failure.

3. New Challenges Brought About by Industry Restructuring

Recently, functional unbundling of regulated utilities has brought about new challenges. In particular, the power grid owners are required to provide equal access to power producers inside and outside their boundaries. This has led to a complete change of the hierarchical operating and planning industry practices. The power grid has begun to be used in qualitatively different ways even during normal conditions. This has created the need for more monitoring, and regional coordination of network congestion, for example. Overall the situation is such that it is no longer possible to forecast conditions based on system operator's knowledge of their own sub-networks, nor is it possible to predict the worst-case scenario at the utility level without better information about the power flows across the region. In addition, some parts of the country have formed electricity markets in which power is traded like any other commodity. This has led to the need for IT to coordinate and secure financial trades and physical network operation in near-real-time. The electricity restructuring experiment has proven to be a much larger challenge than initially imagined. This should not have come as a surprise given that a market of such complexity has rarely been attempted in the past by other industries, and given the unique temporal and spatial challenges. Future leaders are likely going to re-think the fundamental principles of these markets as complex dynamic heterogeneous network systems. This makes the technical problem of efficient and robust electricity services very dependent on regulatory structures, much the same way as is the case in communications networks. It is very difficult to teach this problem in sufficient depth and breadth to ECE students, unless significant re-thinking takes place to conceptualize the key problem formulations.

4. The Newest Challenge — Pressure to Provide Sustainable Energy

The problem of going green is likely to affect future electric energy systems in fundamental ways. Most of the new types of energy sources are non-traditional, and their models are not household items in engineering textbooks. Most importantly, they are intermittent, and essentially prevent operators from knowing with high confidence the power available to meet demand. As part of conservation, demand is likely to become more responsive to system conditions and real—time electricity prices. Novel frameworks and algorithms are needed to cope with hard-to-predict scenarios there is therefore a need for IT-enabled flexible utilization essential for reliable, efficient, secure and sustainable services. Overall, environmentally sustainable energy utilization will require a complete paradigm transformation from a hierarchically operated network to a highly dynamical stochastic open access network.

5. Objectives for Modern Electric Energy Systems Programs

The combined industry changes in terms of technology and organization have brought about new complexity from the highest level system to the smallest level component. The consequent burden on new technical leaders is enormous. Most of all, they must be capable of rethinking how to plan, rebuild and operate an infrastructure which has been turned upside-down from what it used to be. To prepare for such major challenge, leaders must understand 3φ physics (the basic foundations); modeling of complex systems (architecture-dependent models, components and their interactions, performance objectives); dependence of models on sensors and actuators; design for desired system performance (defined by economic policy and engineering specifications); numerical methods and algorithms, and IT, in its broadest sense.

It should be clear that this is not how power engineering of yesterday was taught. The challenge to the faculty responsible for the development of adequate curricula is equally high. They must introduce conceptual problem formulations; understand how models, sensing, control and communication are different for sample systems: (1) old centralized infrastructure; (2) deregulated industry; and, (3) industry with many distributed sensors, controllers, intermittent generation, and demand-side input) There is also a great need to introduce novel simulators/graphics/visualization to teach these concepts. Without such conceptualization it is practically impossible to identify the basic industry innovation needed with a potential to significantly improve the system performance. National research initiatives, such as smart grids, will remain phrases unless a new workforce is trained to rethink industry problems.

6. Modern Electric Energy Systems at Carnegie Mellon

Many institutions have long neglected innovation in ECE education in the area of electric energy systems. At Carnegie Mellon University over the past five years a focused effort has taken place to fill this void. In a relatively short time the momentum was established in both teaching and research. Given the integrated approach to teaching and research both research centers and course/program development took place in the past few years. On the research front we established the Carnegie Mellon University Electric Energy Systems Group (EESG) as well as continuing to pursue technical and policy efforts through the efforts of the Carnegie Mellon Electric Industry Center (CEIC). The number of both undergraduate and graduate students with an interest in this area is high and growing partly in response to the increased visibility of the research efforts in this area. It has become impossible to ignore the grass-root pressure from students for developing the area. Students have become genuinely interested in careers in future energy systems; they are drawn to the area to serve society while still doing engineering.

While perhaps too early to claim success, we would like to share the approach taken in ECE at Carnegie Mellon University. From the very beginning the emphasis has been on formulating the electric energy systems problems as complex dynamic network systems, instead of on studying component physics. Viewed this way, smart grid becomes an enabling network for integrating many new physical components. A great deal of effort has gone into novel modeling for "translating" a physical and business system and its objectives into the language of systems, control, sensors, signal processing, computer science and IT including cyber security. This is possible at Carnegie Mellon University's ECE program given its flexible organizational structure which includes many elective choices for the students throughout their four year B.S. program. Team teaching of both ECE and business and public policy has led to a unique experience of the students as well as providing the expertise needed for this industry. The program is further enhanced by the recent development of an M.S. in Energy Systems spanning all the departments in the college of engineering and including concepts from business and economics and of course the integration of educational efforts with the ongoing research efforts

Sample courses currently taught in ECE are: 18-418 Electric Energy Processing: Fundamentals and Applications; 18-875/19-633/45-855/45-856 Engineering and Economics Problems in Future Electric Energy Systems; 18-618 Smart Grids and Future Electric Energy Systems; and 18-777 Large-scale Dynamic Systems. All these courses are taught with an eye on regulatory, technological changes, and the implications of these on application domain problems: posing open questions and possible solutions. Courses emphasize commonalities across different electric energy systems (power systems such as power distribution to homes; shipboard, aircrafts and cars). In house software development has taken place to support the curriculum. Phase 1 of the (Graphical) Interactive Power Systems Simulator ((G)IPSYS) is now complete, and we are starting Phase 2 which concerns software for demonstrating multi-directional and multi-layered management of future energy systems, which we refer to as Dynamic Monitoring and Decision Systems (DYMONDS).

7. Closing Remarks

There exists now a highly unusual window of opportunity to introduce modern electric energy research and education programs. We are all aware of the obvious societal needs. However, we may waste this opportunity without a full understanding of the potential of embedded IT-enabled intelligence in the new resources and the role of multi-layered multi-directional coordination within the complex novel network architectures. On the educational front it is essential to pose the design and operation of new electric energy systems as the problem of a multiple performance-driven cyber-physical systems over various contextual, temporal and spatial phenomena. This view lends itself to a possible path of truly integrated teaching of future electric energy systems as an excellent real-world example of many concepts taught in more general ECE, policy, economics and business disciplines. Synergic formulations of real-world energy systems based on such a multi-disciplinary systems view is bound to influence future leaders to think holistically.