Control of Energy and Information in Stationary and Mobile Power Networks

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Traditional power/energy systems are slowly but surely giving way to next-generation smart power networks comprising the spatiotemporal synthesis of energy generation, distribution, processing, and utilization nodes along with sensing, computing and communication nodes. The resultant confluence of energy and information has opened up new possibilities in existing application paradigm aside from creating new applications. We outline a few of these research challenges in the emerging domain of stationary as well as mobile cyber-physical energy systems.

To begin with, the lack of a methodology for synthesis of dynamical model for cyber-physical energy systems is an area of great interest. A brief overview of the traditional power system modeling indicates that the dynamical modeling of such systems are based primarily on the premise that electromagnetic transients are essentially insignificant as compared to electromechanical transients and hence often the dynamical model is based on reduced-order smooth nonlinear dynamics with algebraic constraints. However, an overview of emerging non-stiff energy systems such as microgrid and distributed generation indicates that such a modeling philosophy needs a change. Microgrids, for instance, comprise plurality of switching power-electronics systems which do not exhibit smooth nonlinear dynamics. Furthermore, propositions have been made to protect these non-stiff power systems with solid-state controllable fault-mitigating actuators that also exhibit impulsive dynamics. If one further considers the network controllability and the associated distributed delays, it appears that there is a pressing need for a unified modeling representation that can capture hybrid, functional, and stochastic dynamics of not only the emerging stationary/mobile power networks but can encompass the legacy power systems as well.

A logical follow-up to the above is the issue of stability that relates to energy security and reliability. Given the dwindling gap between demand and supply in legacy grid, given the non-stiffness of the emerging microgrid, given the intermittency in energy generation of renewable energy, given the stochastic uncertainties in demand and uncertainties associated with mobile loads in power networks, and given the latency of information exchange, the approach to stability analysis of next-generation power systems cannot rely solely on traditional small-signal analysis or in rare cases on traditional energy-function based Lyapunov function based analysis. New approaches to systematically determining the stability of such nonlinear, distributed, stochastic cyber-physical energy systems needs to be developed that are robust and scalable and yet computationally efficient. While for legacy grid, dimensionality remains the leading challenge to the formulation, for several other power networks wide variation in time scales need to be carefully addressed.

Compared to modeling and stability analysis, research in control of power networks has received wider attention in terms of local as well as global control. Notwithstanding, there are plurality of challenging and yet important issues that need to be explored and addressed. To begin with, given the increasing maturity and reduced cost of microelectronics based intelligence supported with ubiquitous-sensing and pervasive-communication, and distributed-computation capabilities, the approach to control needs to shift towards one that is based increasingly on networked-control concepts with ability to sustain decentralized/pseudo-decentralized operation in the presence of intentional/non-intentional channel interference. In that context, yet another interesting issue is to explore the mechanisms to exploit the capabilities of the cyber layer to the fullest. For instance, instead of treating the impact of distributed flow of information for control in the form of distributed delay and simply compensating for it, what will be more useful is to devise mechanism of control-communication that jointly optimizes control of the power network over the communication network as well as control of the information-flow network itself.

Yet another emerging issue with regard to control of the cyber-physical power networks is the issue of resilience. For instance how to ensure robustness of control in the presence of uncertainty in the truthfulness and accurate representation of the measurement and deliberate corruption of data? Cyber security needs to be an integral part of the control. Using advanced data-mining techniques emergence of undesirable (but known) patterns in the control related data needs to be recognized and addressed at the onset so that the robustness and reliability of the physical power system is ensured. However, for undesirable data patterns that are unknown, the challenge is significantly more. There appears to be a need to co-address the issues of control, data mining, network complexity supported with new and advanced estimation-under-uncertainty approaches.

In the context of resilience, yet another issue that appears to have limited attention is the formulation and synthesis of mechanisms that unify protection and control. Traditionally, protection is mostly local and primarily leverages experience and abundant caution with an eye on the reliability of the power system. Rapid advancements in high-voltage and wide-bandgap device technologies that can support ultra-fast switching with multi-resolution controllability have now enabled the possibility of incorporating an added (faster) layer of protection to the hierarchy and functionality of control. Since protection has a temporal as well as a spatial element, control using ultra-fast solid-state switching combined with pervasive event- and need-driven communication can revolutionalize fault tolerance and self-healing of legacy and next-generation power networks.

While the list is abound as to the research challenges within the framework of existing cyber-physical energy systems, it is noted that some of the above-referenced advancements pave the way for completely new applications as well. For instance, the first author has recently proposed a completely new way of transferring energy in an interactive power network such as a microgrid. This new patent-pending mechanism – referred to as Boolean microgrid – enables the discrete instead of continuous transfer of energy as well as information over a common link paving the way for a radically different cyber-physical energy system. The core idea is to support need-based energy transfer from the distributed energy resources to distributed loads over a high-frequency-link network to ensure dynamic power balance and management. The central idea can also be extended to systems where physical link of discrete energy and data transfer is not wave-guided but free space. Such cyber-physical energy systems can include wireless vehicle-to-vehicle dynamic energy transfer (for enhanced mobility and transportation range) or transfer of energy among mobile robots to enhance their operating lifetime and yield new mechanisms for path-planning, maneuvering, and controllability. Such emerging mobile power applications will enhance the scope of research in cyber-physical energy systems, currently focused primarily in stationary power systems, paving the way for new science and technology that deserves closer attention and enhanced support.