Position Paper

Energy CPS Network Science

2013 National Workshop on Energy Cyber-Physical Systems

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Electricity and natural gas networks are two prime examples of energy networks that are large, complex, interactive, and are on the cusp of major transformation. Motivated by sustainability, the need to utilize renewables, and increasing demand, cyber-centric tools are becoming increasingly necessary in both of these large energy networks and can be viewed as prime examples of Energy-CPS networks. Natural gas currently fuels a large portion of the electricity generation portfolio of the United States, and this is increasing as compliance with environmental regulations reduces the number of power plants with high greenhouse gas emissions and/or prohibitive regulatory requirements and lead times. Because renewable energy availability varies due to normal daily and even hourly fluctuations in wind and sunlight, fast-response natural gas fired generators can balance power fluctuations. These generators can also regulate grid voltage and frequency, which is necessary to tap the full potential of renewable energy. Tighter coordination and information sharing between electric grid operators and gas suppliers, and technology advancements are key factors to ensure adequate gas supply to generators.

While both networks possess several common features such as size, complexity, interconnectivity, and stringent performance goals, they are strikingly disparate when it comes to their time-scales and constraints, not to mention the underlying physics. The following are noteworthy:

- Electricity moves at the speed of light while natural gas travels 40–60 miles per hour.
- Electricity is not a storable commodity. So, the contingency-constrained network flow operation could preclude transmission systems from utilizing their maximum capacity. The ability to store gas in tanks and in pipelines alleviates this problem for gas. Natural gas utilities typically rely on the natural gas storage to augment supplies flowing through the pipeline system and to meet the total natural gas demand throughout the year. A natural gas system designed to meet peak demands that does not include storage would be significantly more costly.
- Economies of scale are very large in electric power transmission projects. It is much cheaper to install the required capacity of a transmission line initially than to retrofit the line later. However, gas pipelines are commonly operated at a lower pressure and the pressure is raised later to obtain additional capacity.
- Natural gas pipeline flows can be controlled independent of the gas network constituents. However, it is neither economical nor practical at this time to control individual power transmission segment flows.

The nature of the physics, underlying storage and flow structure seems to indicate that the time-scales associated with natural gas are much slower than those of the electric network. That the two complex networks are interconnected and need to interact synergistically is clear due to the increasingly important role of fast response natural-gas fired generators in the face of renewable integration. Equally clear is the need for cyber-enabled tools as the emergence of concepts such as demand response, advanced metering infrastructure, and increased deployment of feedback and communication are enabling the realization of lofty goals of efficiency, reliability, and resilience. This in turn implies that the underlying problem is the design of energy-CPS networks such that the physical infrastrucutres interact using a cyber-substrate and realize desired goals.

Research needs to be carried out therefore in the area of energy CPS networks, with hybrid characteristics. The effect of disparate time scales, the design of interactions that exploits these time-scales, dominant constraints that govern the interactions between these networks, and the effect of uncertainties on the interactions need to be studied. Properties of consensus, cooperation, and coordination as well as stability, robustness, and resiliency have to be analyzed and design guidelines for the interacting energy networks have to be suitably synthesized.

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