Research Challenges in Information Systems for the Next Generation Electric Grid

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Abstract: The lessons of network-centric information systems design are vital for the successful development of a 21st century electrical energy grid. We highlight four key research challenges associated with the design of the future energy grid derived from our perspective as contributors to the evolving distributed computing and middleware infrastructure basis for network-centric cyber-physical systems: methods and protocols for integration of independently created and managed subsystems and components; information services such as aggregation and de-aggregation of data sources; control of information flows that cross administrative domain boundaries; and system agility and robustness against malicious participants. Finally, we elaborate on some starting points for investigation that cross-cut these.

R&D challenges and opportunities for building the next generation of high-confidence energy cyber-physical systems lie in each of the following areas of emerging need:

- *Methodologies, frameworks and protocols for interoperable smart grid design*

There is a need for designs, algorithms, and methodologies to support the development of grid-based cyber-physical information system services that integrate across multi-level and system of systems abstractions, built at different times by different entities, yet that function together, properly inter-operate, and coordinate as a managed “system” at each level. This fundamentally reflects the nature of the interrelationships associated with national, regional, and local level concerns and widening the spread of diverse suppliers across more managed demand. Frameworks and protocols incorporating information management interoperability at multiple levels of regulatory, policy and control, reliability, and quality of service will enable independently manufactured and administered collections of new or existing equipment to more easily integrate and coordinate with other participants into and across local, regional and national “systems” in a vastly simplified manner. This can be expected to effectively lower the barriers and cost of new deployment. We anticipate the need to support models which incorporate combinations and hybrids of both hierarchical and peer-to-peer relationships. This multi-layer system view applies equally to the domain of the controlling information system as well as to the domain of the electrical power being generated, consumed, (potentially) stored, and managed.

- *Information services for a smart grid*

In order to serve the need of broader information sharing in the future electrical grid there is the need for enabling techniques that focus on the multi-granular uses and consequent aggregation/de-aggregation of information. Added to this is the compositional nature of the individual layer contributions toward larger end-to-end managed system properties. In the future electrical grid, utilities operating at the same local “layer” may need to share information, for example about local phase measurements in an effort to anticipate grid failures. Common services, such as those needed for observation/monitoring, control, protection/assurance, and adaptation, will have both a domain of an individual layer or embedded “system”, toward managing a local solution, as well as being part of a larger set of solutions at another granularity and for another domain focus. Information can be aggregated to derive specific properties (e.g., overall usage patterns or supply and demand trends for particular classes of users), with the ability to trace back to the constituent elements, for example for control purposes. Or it might represent just averages or aggregate observational properties for compliance without consequent de-aggregation. Composition of components of multi-layered solutions into an over-arching system property brings with it the need to manage system properties as they pass through the components, making them both visible and controllable, along with the needed standards.

- *Federation and cross-domain issues in a smart grid system of systems*

An important new aspect of investigation lies in federation and "cross-domain solutions". By that we mean a focus on integration and interoperation techniques and technologies to control information access and flows as they cross significant organizational boundaries. For example, utilities' operational loads would benefit from sharing with ISOs' (or other regulatory entities) and each other for improved end-to-end system management. There is already expected to be a substantial information system infrastructure independently developed. The purposes of the interconnects in these cases are to feed and support the coordination and higher granularities, such as regulatory or market considerations, while not necessarily exporting control or even promoting openness. There is already ongoing investigation and limited experience with cross-domain technologies that enable information discovery and brokering with appropriate access control in highly dynamic environments crossing multiple information and security enclaves. However, the domain specifics of sharing in the energy arena are sure to be influential here.

- *Agility and survivability of a smart grid system*

Adaptive and survivable system design, both subjects of considerable current activity, will take on even more importance when applied to dynamics of critical energy generation and delivery. The strict synchronization requirements of the grid place a strong emphasis on timely and accurate dissemination of information, often across long distances. While we anticipate the emergence of services to support adaptive Quality of Service (QoS), these would need to be applied specifically to the most demanding precision and continuity needs of the innermost control loops, which are dependent on underlying physical equipment constraints. It is important to be able to incorporate multi-level monitoring and QoS controls that rapidly recognize limitations in the ability to deliver power, excessive demand, failures, and underutilization, and respond rapidly, in order to compensate, recover, and reconfigure to keep a steady and reliable flow of power where it is needed. The area of cyber-security, inclusive of protection, detection, continuous operation, and even regeneration in the face of losses, is especially germane. As we have demonstrated with a multitude of adaptive networking designs, the adaptation mechanisms introduced to improve efficiency or to satisfy QoS service level agreements can themselves be exploited not only by adversarial users of such systems, but also by rational, greedy stake holders who are only interested in optimizing their own utility, independent of any desirable system properties. This motivates the need to be able to constrain specific users, and develop approaches intended to minimize misuse or abuse. Current research in survivable system design is exploring temporal and spatial containment techniques that can be leveraged in this domain. Along with enabling smart grid dynamic behavior also come the challenges of confidence and certification that these will indeed work as advertised, even under unanticipated circumstances. The current economic situation is a reminder of some of the downside and unintended complications of unmanaged interconnected complexity.

Next, we expand on ideas which cross-cut these areas of investigation with a particular focus on the challenge of service aggregation/de-aggregation for future energy systems' interactions with households and small businesses. Although the contribution of each such "micro-participant" is insignificant, effectively packaging and controlling the aggregation of many millions of these micro-participants could constitute a significant impact fraction of the total energy consumption.

At present, the aggregate of micro-participants is effectively uncontrollable except by crude measures such as rolling blackouts, static pricing and mass-media appeals for conservation. The aggregate of micro-participants have significant potential to be harnessed, however, if manageable fine-grained monitoring and control relationships can be established between the bundle of micro-participants and the information and energy supply and distribution infrastructure with which they interact. As examples, the inherent flexibility of many end-user needs could be captured to produce "painless peak-shaving" through personalized response of a micro-participant's devices, and micro-generation and distributed energy storage (e.g., in plug-in hybrids) could be coordinated and managed as "virtual power plants".

Creating such control remains a challenge in establishing aggregation and de-aggregation services. On the one hand, information from millions of micro-participants and their electrical devices needs to be combined to form a model of the aggregate. On the other hand, control signals to that model need to be decomposed and distributed to act on individual devices. This challenge is complicated by the fact that there are many participants, yet monitoring and control need to potentially occur on very short time-scales. Other major concerns are safety (avoid system instability), security (ensuring that system behavior cannot be corrupted by injection of bad monitoring or control signals, either by an attacker or a malfunctioning device), and privacy (ensuring that information about participants is not exposed by the aggregation and de-aggregation process) as outlined in the list of challenges above.

The scale and concerns for these challenges make it difficult to apply conventional techniques for aggregation and de-aggregation as a service to the system. Collecting all communication to a single point/single server farm where all of the computation takes place is made difficult by the scale, and leaves the system fragile to failures, while actually increasing the privacy problem. Setting up a hierarchical aggregation/de-aggregation network improves the privacy and scaling problems, but still leaves the service fragile because there are more points of attack but little in the way of redundant information channels. There are alternative approaches that show promise such as those associated with utilizing spatial computing techniques.

New supply side aggregation issues appear as well. Distributed generation and the introduction of various forms of micro-grids lead to a future of combined stable (traditional) as well as many less predictable (green) sources. This may require an integrated way to derive reliable and predictable behavior out of combinations of this large number of smaller and more variable suppliers. Factors like the damping effect of uncertain supply units, the percentages of stable and uncertain supply in the mix, and storage elasticity of the bundle need to be considered. The problem lends itself to hierarchical control loops: within an aggregate, new demand side control capabilities can be leveraged to manage the deviation of the actual demand/supply from the projection to a greater degree before engaging more costly responses; an outer control loop can balance excess supply, as available, across the aggregates. One could envision a third introspective control loop that will learn over time to improve the estimation and control logic through pattern discovery and identification. Comprehensive research in multi-level control, adaptive decision making and machine learning can be brought to bear in developing such advanced control regimens for the future smart grid, bearing in mind the safety of the overall system.