Optimization and Control Theory for Smart Grids

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Primary Grand Challenge

- **Information Science and Technology**
  Applied Priorities (in the order of relevance):
  - (a) Inference / Prediction
  - (b) Data Intensive Computing

Budget request for FY10, FY11, and FY12, in $K

- FY10: $1650K
- FY11: $1650K
- FY12: $1650K

Science and Technology Objectives

The basic structure of the electrical power grid has remained unchanged for a hundred years. It is a hierarchical, centrally-controlled structure that assumes that power is generated solely from large central facilities, that power is abundant, and that power generation is relatively benign. Stability is attained through redundancies and highly controllable generation that reacts to problems such as demand fluctuations and outages, rather than anticipating and avoiding them.

A number of significant developments have upended the assumptions under which the current grid was designed. Demand has risen sharply, and will continue to do so. Science has shown that we need to curtail or eliminate our use of the most abundant sources of power, fossil fuels, in order to avoid severe environmental consequences. Alternative sources of energy from renewables, such as wind and solar, are available, but are often distributed, intermittent, and thus, difficult to control.

These developments are forcing a paradigm shift in the structure of the grid. The essence of this shift is that tools of information technology are being introduced to improve the efficiency and stability of the grid, and to facilitate the use of distributed generation from renewables. A future grid, in which modern sensors, communication links, and computational power are used in concert to improve efficiency, stability, and flexibility, has become known as the *smart grid*. The new administration [1] and the Department of Energy [2] both recognize the need for a smart grid, and the total national investment in the grid is expected to top $2 trillion over the next twenty years [3].

Much of the hardware that will enable this revolution is in development or already exists: "smart" meters and appliances that respond to pricing signals; distributed wireless sensor networks; improved batteries for plug-in hybrids that enable distributed storage, and so on. What is largely lacking, and what this project intends to provide, is a fundamental understanding of how best to wed information science and technology to the electrical grid. The smart grid is now at the stage of telephony when the first telephones were invented. The potential was obvious, but the realization of this potential required extensive developments in communication and switching theory, of which information theory itself was a spinoff. In the same way, information technology will be essential in realizing the full potential of the smart grid.

The purpose of this project is to develop algorithms for optimal design of the nation's next generation power transmission and distribution system that will incorporate the new realities of the grid. Our ultimate goal is an *innovative suite of real time capabilities for detecting and preventing instabilities and outages and a state-of-the-art framework for analyzing and designing the smart grid and associated control network*.

Tasks and Probable Accomplishments

We will use our expertise in information science to solve problems in four areas key to an integrated analysis of smart grids: *grid robustness*, *grid design*, *grid control*, and *grid regulation*.

Grid Robustness — How do we protect against fluctuations and outages? To address this problem, we will develop an extreme events analysis framework for detection of rare but devastating outages, based on the powerful *optimal fluctuations* approach that was developed at LANL recently. Our goals are to detect failure modes of loads on power graphs, predict the probability of coherent failures at medium- and large-scales, heal or stabilize the damage by identifying locations for load shedding, and reduce the outages by smart control. To this end, we will utilize our expertise in algorithm accuracy and efficiency. The analysis will also allow us to determine the impact of intermittent generation on the existing grid and evaluate mitigation strategies. Since outages spread very quickly, the algorithms must operate in real time to enable effective countermeasures.

Grid Design — As the grid expands, what is the best placement for new renewable and storage facilities, and what are the optimal choices for decommissioning aging facilities? What are the tradeoffs, in expense and reliability, between a tightly connected lattice and a loosely connected tree? Are there stability issues that arise from distributed generation, and if so, can stability be achieved through specific topologies? These questions involve tradeoffs between competing objectives, such as cost, size and stability, and can be addressed through techniques of multi-objective optimization. Figure 1 shows an example of options that might be considered in Florida. The grid can be analyzed at many different scales (Figure 2), which have significantly different characteristics. We will address the problem of grid design at each of these scales.

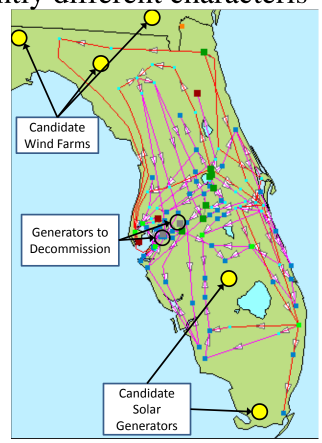

Figure 1: Options for placement of renewables.

Grid Control — Can centralized control be replaced with distributed control? Is distributed control essential in the presence of distributed generation? What is the optimal scale or scales for control of the grid? What are the implications for grid stability? Given a local domain, how much information about neighboring domains and how much predictive capability is essential for effective control? To address these problems, we will model the grid dynamics at multiple scales. We will identify information theoretic capacities that will characterize the value of information for prediction and control. We will use these analyses to determine communication requirements for effective control, and to identify thresholds at which additional information is of little value.

Grid Regulation — What regulations are needed to ensure an electricity market that is both efficient and resistant to manipulation, while preserving the grid reliability? Much of the promise of the smart grid comes from its potential to provide financial incentives for certain behaviors, such as reduced consumption, consumption at off-peak hours, use of renewables, and so on. How effective are these measures, and what are their consequences for reliability? To address these problems, we will expand our bounded confidence model and optimal pricing theory to account for price variations, consumer response, consumer interactions, and demand-side management of smart grids.

Several Information Science and Technology (IS&T) tools will be developed in support of multiple tasks. Existing grid characterization and simulation tools are not adequate for the emerging smart grid [2], and a major part of our effort will be to develop and implement new algorithms that will overcome the limitations of existing approaches. A key effort, which will serve the first three tasks, will be the development of reliable state estimation algorithms based on statistical models of demand, intermittent generation, and grid fluctuations verified against actual data.

Another enabling tool, which is relevant to all of the tasks, is an algorithm to perform optimal matching of supply to generation, based on reliable prediction of generation and market-controlled consumption. The development of such an algorithm is an unsolved problem, which is comparable to the computationally hard unsolved problems in inference, optimization, and control [2]. This task will require deep insights in the areas of mathematics, statistics, and numerical methods. We will state the underlying optimization and control problems of the smart grid in modern graphical terms, allowing us to produce efficient algorithmic solutions through graphical model and stochastic techniques, a topic on which members of our team have produced major breakthroughs.

We have outlined an ambitious research agenda and a bold vision for aligning the broad set of information theory and infrastructure modeling capabilities at Los Alamos with the emerging smart grid technology. We trust that we have solid prospects for advances in the proposed tasks. In particular, our recent algorithmic developments should be directly applicable to analysis of grid robustness. We emphasize that the the economic scale of the electric grid is so enormous that even the smallest advances in efficiency or renewable integration will yield huge financial payoffs.

In all of the tasks, our methodology will be to (i) develop models of the grid that abstract out the essential features of the particular problem, (ii) analyze the models using analytical and numerical methods, and (iii) develop new algorithms, with guaranteed accuracy bounds, for solving these models.

When appropriate, the algorithms will be incorporated into the existing LANL Interdependency Environment for Infrastructure Simulation System (IEISS) through the Hydra modeling and simulation architecture [5] and validated on the data available inhouse through the National Infrastructure Simulation and Analysis Center (NISAC) and via collaboration with PNM and NREL. In particular, we will expand the current IEISS simulation capability to include intermittent renewable generation, thereby placing LANL in a competitive position for assessing smart grid vulnerabilities (Figure 1 is based on IEISS data).

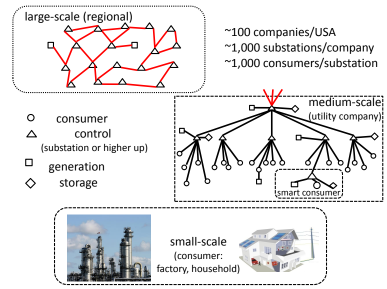

Figure 2: The network involves many different scales.

Institutional Goals and Objectives

Development of IS&T tools for smart grid is fundamental to the DOE mission. The outlined challenges are aligned with focuses of the new Information Science and Technology and the Energy Security incubation centers at LANL. This work utilizes our existing theory capability in statistical analysis of complex stochastic systems, networks, and graphs developed in recent years via LDRD projects and active external funding from NSF and UCOP. The results of this work will position LANL competitively for new infrastructure analysis and simulation capabilities and expand the customer base beyond DHS to the DOE smart grid initiative [2].

Our team is well-balanced between the theoretical areas of computer science, optimization theory, machine learning, operations research, information theory, control theory, statistics and non-equilibrium physics, and the more applied expertise in power engineering, energy hardware, energy planning and policy. We will partner with PNM, hosting site for a smart grid demonstration project [4], and NREL. Our research and educational outreach with MIT LIDS and Energy initiative, EECS Departments of U of Minnesota, U of Wisconsin, U of Texas Austin, U of Vermont, and Penn State will help to bring new talent and expertise to LANL in Information and Energy Sciences. For additional information, see `http://cnls.lanl.gov/~chertkov/SmarterGrids/`.

References

[1] `http://int.lanl.gov/news/index.php/fuseaction/nb.story/story_id/15665/nb_date/2009-02-05`; [2] `http://www.doe.energy.gov/smartgrid.htm`; [3] `http://money.cnn.com/2009/01/06/news/economy/smart_grid/`; [4] A letter of intent from PNM establishing interest and a commitment to collaborate on validating our approaches on their smart grid hardware; [5] `http://dev-y.lanl.gov/projects/hydra/`.