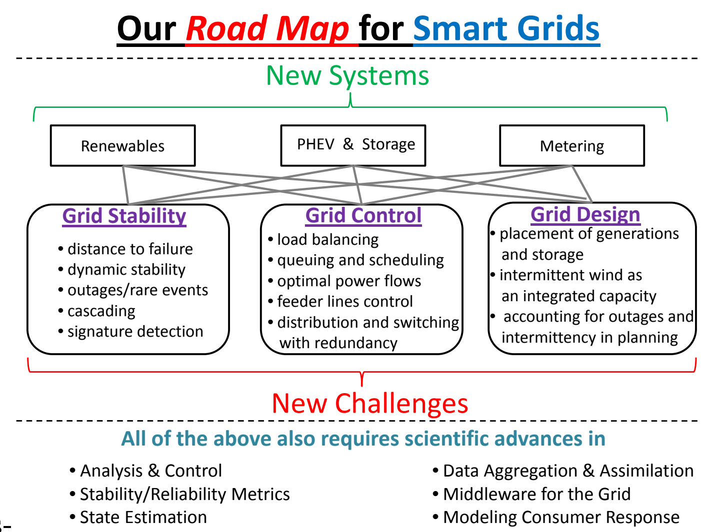
# Optimization and Control Theory for Smart Grids

*Grand Challenge: Information Science and Technology*

## I. Research Goals and Objectives

The basic structure of the electrical power grid has remained unchanged for a hundred years. It has become increasingly clear, however, that the hierarchical, centrally-controlled grid of the twentieth century is ill-suited to the needs of the twenty-first. A future grid, in which modern sensors, communication links, and computational power are used to improve efficiency, stability, and flexibility, has become known as the "smart grid." Much of the hardware that will enable smart grids is in development or already exists: "smart" meters and appliances that respond to pricing signals, distributed wireless sensor networks, improved batteries for plug-in hybrid electric vehicles (PHEVs) that enable distributed storage, and so on.

The new administration [1] identifies energy as one of the top three national priorities, education and health care being the other two. Furthermore, smart grids and renewables are the centerpiece of the national energy agenda. The national laboratories are now called upon to provide the science and technology base required to make the smart grid a reality and to provide an independent technical assessment on how to best deploy smart grid technologies. The Department of Energy, in its modern grid initiative [2], outlines a forward looking agenda with a complex set of challenges and requirements for the smart grid. Los Alamos National Laboratory, with its technical capabilities in infrastructure analysis and information theory, is poised to become a major contributor to this national grand challenge. Indeed, while much of the needed hardware necessary to enable the smart grid may be in place, the *Information Science and Technology* (IS&T) foundation for the smart grid design, operation, and risk assessment requires major development.




Our road map is driven by emerging technologies such as renewables, storage, and meters and accordingly specifies the technical challenges in *Grid Design*, *Grid Control* and *Grid Stability*. Rather than tackle the full complexity and requirements of the grid, from security to operations to pricing, we focus on a clearly defined subset of problems where we have well-developed IS&T capabilities, and where we can have the strongest impact. In the area of Grid Design, we study efficient and robust integration of geographically distributed renewable generation by solving cutting-edge optimization problems that incorporate difficult constraints imposed by the transmission of electrical power. In Grid Control, we consider two load balancing problems in the low-voltage distribution grid: development of robust and efficient distributed control techniques and algorithms based on queuing theory to enable high penetration of small-scale distributed generation and plug-in hybrid vehicles. In Grid Stability, we will develop a toolbox capable of detecting instabilities and failures for preventing costly outages. All three problems require the development of efficient new algorithms.

To address these most pressing smart grid IS&T challenges, we will aggressively utilize and further develop existing LANL expertise in analysis and control, stability and reliability metrics, and state estimation. We will also develop new capabilities in data aggregation and assimilation, communication middleware for the grid, as well as modeling of consumer response.

# II. Proposed Research

Our proposal of optimization and control theory solutions for smart grid problems stresses the need for efficient new algorithms. We outline a specific set of problems where our extensive preliminary research [5-15] provides a compelling case for the proposed algorithmic approaches. We note that there are obvious connections between the three focus areas. For example, improved grid stability is an objective for grid design and similarly, improved grid control yields a more reliable grid.

## Focus Area 1: Grid Design

A key challenge in creating the smart grid is determining where to place new transmission, generation and storage facilities. We will answer the short-term tactical question of where best to situate new facilities, and develop a long-term strategy of how to optimally evolve the grid structure through algorithm development.

Renewables generation, such as wind and solar, are intermittent. Moreover, regions where wind is plentiful, such as the great plains in the US, often lack adequate transmission lines. Effective and safe exploitation of renewables requires planning. The National Renewable Energy Laboratory (NREL) WinDS project [3, 4] is the state of the art in planning and placement of renewables. While the WinDS model is an excellent first step, it does not account for power flow stability or grid resiliency.

We studied the WinDS solutions and discovered that they often result in a highly unstable electric grid (Fig 1) and undesirable power-flow loops. Our analysis [5] suggests that the problem is in generating globally optimal solutions that accommodate intermittent renewable generation. We will address this challenging problem using two approaches. First, building on the work of [16], we will develop improved network optimization approximations and second, we will investigate hybrid algorithms. The first approach is potentially more powerful but less mature than the second one already tested on field data. The two approaches naturally complement one another: the first provides an excellent approximation to the long-term addition of renewables and transmission and provides a starting solution for the second approach.

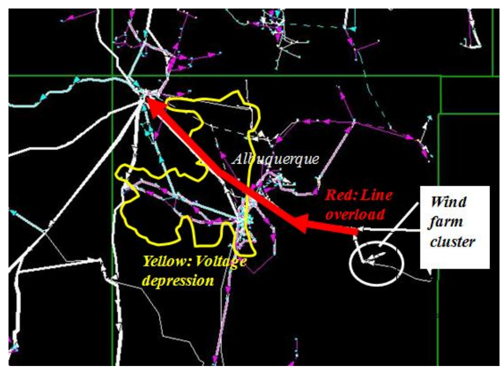



Figure 1: An unstable grid example.

**Network Optimization.** The grid is represented as a graph. The nodes of the graph are the contemplated generators, storage, interconnects or demand units. The edges of the graph, namely the connections between the nodes, are the transmission lines. We seek the optimal placement of transmission lines for a given set of nodes. Let $y$ be the vector of conductivities or equivalently, inverse resistivities, and $J$ the vector of currents being injected or consumed at each node. Then the simplest problem, stated in terms of resistor networks (which is related to a linearized, or DC, load flow approximation with resistive losses accounted in the first

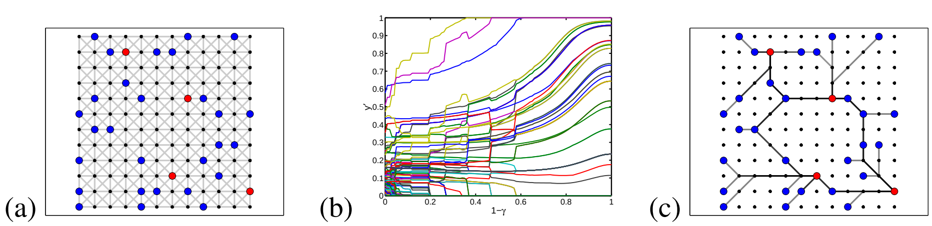


Figure 2: (a) The grid $G$ showing allowed lines (between nearby grid points), locations of generators (red nodes) and loads (blue nodes). (b) Plot of optimized conductivities $\tilde{y}$ as the control parameter $1-\gamma$ is varied from 0 to 1. (c) The sparse solution for $\gamma = .01$.

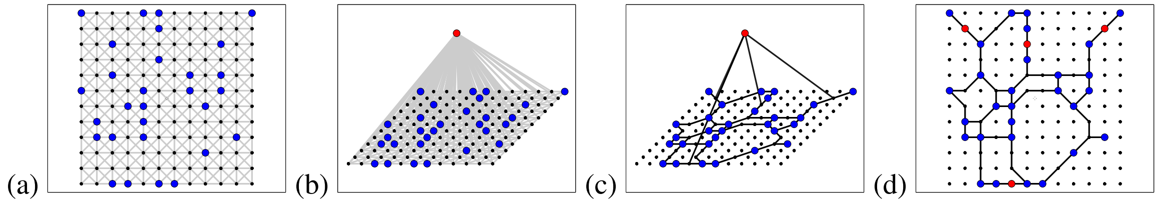


Figure 3: (a) Grid $G$ showing allowed lines (between nearby grid points) and locations of loads (blue nodes). (b) Extended network including "master generator" connected to all possible generator sites. (c) Sparse network obtained by optimization procedure. (d) Corresponding optimized placement of generators (red nodes).

order), can be framed as the problem of minimizing the cost function, $J^T \cdot K^{-1}(y) \cdot J + \sum c_i \tilde{y}_i^\gamma$, with respect to the conductivities $y_i$ from the ranges $[0, y_i^{\max}]$. The first cost term is the network generalization of the familiar formula, $P = VI = I^2R$, representing power dissipation within the grid. Here, $K(y)$ is a sparse network conductivity matrix that depends on the graph topology and has edge weights dependent on the conductivities $y$. The second cost term accounts for the cost of building the transmission lines spread over the lifetime of the line with $c_i$ the effective cost per line. The normalized conductivities $0 \le \tilde{y}_i \le 1$ are defined via $\tilde{y}_i \equiv y_i / y_i^{\max}$, and $\gamma$ is our control parameter. Hence, the cost function models the tradeoff between the cost of the dissipated power and the cost of the transmission lines.

Our results [6], shown in Fig. 2, are illuminating. The parameter $\gamma$ varies from one to zero, and models economies of scale. When $\gamma = 1$, the cost is linear: doubling the capacity doubles the price. A more realistic model is given by a small $\gamma$, where the cost rises abruptly with the addition of a new line, even if $\tilde{y}$ is very small. Intuitively, we expect that smaller values of $\gamma$ lead to sparser networks. The value of this concrete model is that it enables us to determine the optimal sparsity quantitatively. The algorithmic approaches are quite different in the two cases. When $\gamma = 1$, the problem is convex and has a single, easily-computed optimum. When $\gamma < 1$, the problem is non-convex and there are possibly many local minima, which requires the use of simulated annealing type algorithms. The complexity of the latter model faithfully captures several facets of the complexity of the real grid.

We plan to generalize our network optimization model in several ways. First, the currents $J$ can be considered random, thus accounting for variability in consumer demand and intermittency in renewables generations. Furthermore, there are different types of nodes, endowed with different state variables and in turn, the generalized conductivity $K$, will be a function of these variables. Second, we will extend this approach to incorporate optimal placement of generators and to balance loads between multiple generators. In Fig. 3, we show how to place generators using a fictitious global "master" generator that is connected to potential future generation sites. Including the cost of the additional lines from the master generator, we solve the sparse network design problem in this extended network, and determine the optimal generator placement. Our results suggest that it is feasible to find near-optimal network designs within the DC power flow model. We will extend this work to: (1) incorporate convex constraints to avoid overloaded lines, (2) estimate the most dangerous outages and mitigate against these through design, (3) generalize to the full non-linearized, AC, power flow equations, and (4) extend the optimization approach to explore multiple low-lying local minima using simulated annealing with random searches.

**Hybrid Optimization and Simulation.** Our second approach is heuristic and avoids the difficulties of building nonlinear equations into traditional optimization frameworks. Hybrid optimization is cutting-edge in operations research [17], but the use of simulation is largely unexplored in optimization. Our method is a local-search heuristic that utilizes simulation to choose local moves [5]. This *simulation-guided optimization* employs an AC solver that simulates the electric power network and successfully discovers feasible infrastructure networks solutions by starting from the infeasible solutions posed by [3]. The iterative structure of this hybrid algorithm is illustrated in Fig 4 where $S$ is the function that returns a set of physical violations. Starting with a WinDS solution [3], our algorithm manages to add approximately 3500 transmission components and eliminate all voltage violations and line overloads in merely 3,000 iterations (100 CPU minutes).

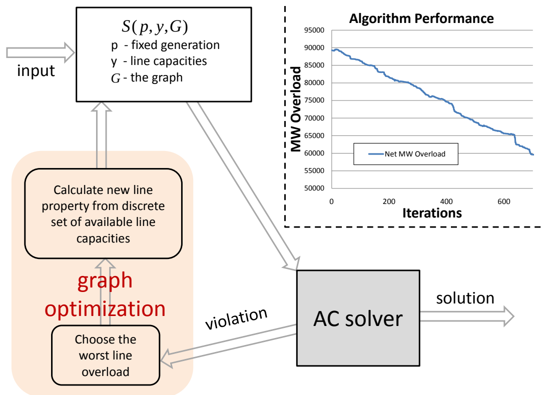



Figure 4: The Abstract Network Design Optimization Algorithm and sample algorithm output.

These preliminary results show that our approach can successfully determine optimal placement of renewables generation facilities. We plan to embed this algorithm into traditional local search approaches and develop new neighborhood exploration procedures that exploit the information provided by the violation function to efficiently find high quality solutions. Our algorithms provide optimal ways for adding a large set of generators over a much larger time horizon, whereas the existing methodologies address the simpler problem of incremental addition of generators.

## Focus Area 2: Grid Control

The primary task in control of the grid is the so-called load balancing problem, namely, matching electrical generation with power consumption. If load exceeds generation for a long enough period, frequency shifts or voltage changes trigger protective equipment with the undesirable consequence of load shedding. Currently, the outputs of generation plants are adjusted to match a highly-variable consumer demand profile with a large peak in the afternoon and a valley at night. In this generation-side load balancing, grid operations and performance would benefit from a load redistribution that “shaves” the afternoon peak and “fills in” the night time valley. The anticipated introduction of plug-in hybrids is bound to amplify the afternoon peak [18, 19].

However, this goal of smoothly filling in the night valley will change as the generation mix evolves from tightly controlled central generation to include renewables with rapid swings in output. Moreover, as communication and control becomes more commonplace on the distribution-level smart grid, PHEVs and other controllable discretionary loads will provide the grid operator with a fast distributed control mechanism for matching load to generation. Hence, the technical challenge is development of efficient and reliable algorithms for load redistribution and fast distributed control.

We first discuss our plans for development of optimal schemes for PHEV charging using queuing theory methods. Second, we outline distributed control where active reconfiguration of distribution grids achieves local load balancing thereby minimizing the impact of local renewables generation on the rest of the grid.

**PHEV Management and Queuing Theory.** If PHEVs were to simply charge “on demand”, the distribution-level system would quickly overload in the evening as consumers return home. As more PHEV’s are added to the system, smart control must be distributed in a way that maximizes the aggregate PHEV charge, avoids overloads, fills in the night valley, and is robust. Some schemes achieve redistribution using variable pricing as well as heavy communication between PHEVs, grid operators, and utility middlemen [20]. We take the view that less communication leads to a more secure and robust system, and we strive to minimize the amount of communication necessary to manage PHEV charging while maximizing charging capacity. Thus, as a first step, we focus on no-communication algorithms for scheduling PHEV charging times. Assuming that the distribution system has enough capacity to charge $m$ PHEVs simultaneously, we assign to each PHEV a random arrival time. We also assume each needs a random amount of time to reach full charge. We estimate the charging capacity as a function of reliability using queuing theory. The number of PHEVs that need to be charged determines the arrival rate of PHEVs, and the average charging time determines the departure rate. Queuing theory [21] provides a method for computing the probability of having $n$ PHEVs charging simultaneously, and we compute the total probability of having $n > m$ for a range of arrival rates, namely, the probability of an overload as a function of the number of PHEVs charged per night, $N$. Figure 5 expresses the average number of overloads per 10 years in terms of $N$ for few values of $m$ ranging from 10 to 30. As expected, the overload rate increases with $N$ for a fixed system capacity $m$, and $N$ increases with capacity $m$ at a fixed overload rate. This simple scheme is robust because it requires neither communication nor coordination between consumers, and sets a lower bound on the number of PHEVs that can be charged overnight for a given overload rate.

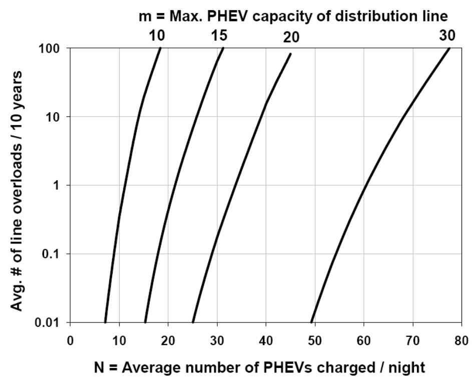



Figure 5: Overload probability for a M/M/m queuing model of PHEV charging, where $m = 10, 15, 20, 30$.

This control scheme is robust but not efficient as the average utilization of the available capacity $m$ is low and ranges from 20% to 40% depending on $m$. As more PHEVs are added to the system, smarter control schemes will be required to increase utilization. In our simple case, the overloads are caused by relatively rare events when $n$ fluctuates well above its average and exceeds the capacity $m$. We will develop schemes that reduce the variance in $n$ so that the average $n$ can be run closer to $m$ while still maintaining a low probability of overload. These schemes could include breaking the charging events into short fixed lengths to prevent multiple PHEVs with long charging times from connecting simultaneously. However, the departure times are no longer random and the queuing problem becomes more challenging although still tractable. We will also introduce basic communication to assess the current system utilization and reduce the PHEV arrival rate as utilization increases. The problem becomes more challenging because the arrival rate is now correlated with system utilization. Furthermore, we will investigate the various PHEV management schemes.

**Distributed Control for Active Grid Management.** Widespread use of PHEVs and redistribution of their loads smooths the consumer load profile by filling in the night valley. This type of load redistribution is valuable given today's centralized, tightly controlled generation. As the generation mix moves away from centralized plants to include more uncontrolled distributed renewables generation, grid operators will need new tools to rapidly adjust *load to generation* and perhaps control the charging and discharging of electric storage units including PHEVs. Many of these swings in generation are too fast for a human to manage. In addition, the number of individual loads on the system are vast and geographically widespread so that *centralized* control of individual loads becomes infeasible.

The existing distribution system already contains remotely controlled switches that reconfigure the grid and readjust performance in response to system failure and outages. Additionally, international consortia have commissioned studies of automated switching to improve system performance, efficiency, and stability, thereby relieving the grid operator of repetitive tasks [22]. We will pursue advanced control schemes including distributed control where local control inputs are computed using measurements and dynamical models, and where the distributed controllers can exchange information with and receive guidance from an automatic transmission control operator [23]. We will employ this control scheme to actively reconfigure the distribution grid to match load with distributed generation and energy storage.

Our pilot study [7] demonstrates a promising technique for distribution-level problems where additional automated switches and ancillary connections are placed into the distribution grid. This capability enables the distribution grid to move from passive operation to a dynamic operation with local load balancing that maximizes local use of renewables generation. Here, control is equivalent to a local search for optimal switching of loads between generators in the system. Figure 6 illustrates such a distributed system where the control

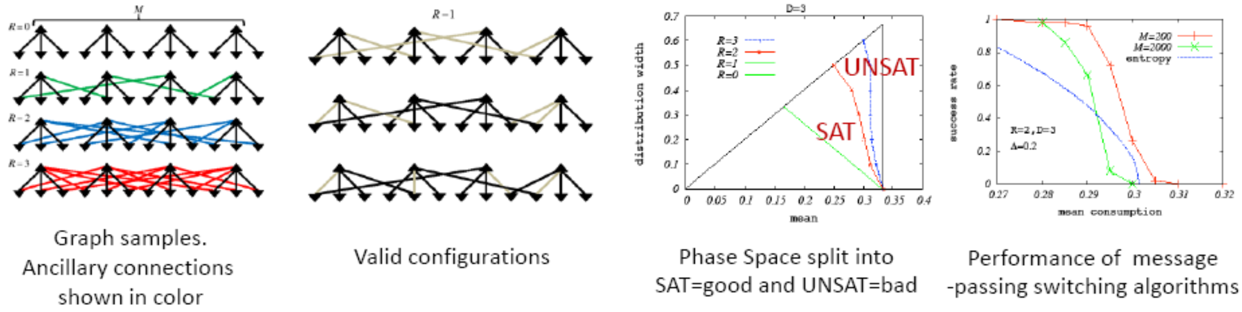



Figure 6: Optimal switching to balance local overload globally without shedding [7]. *M* is the number of generators. *R* is the redundancy parameter. On (c) lines separate the upper right UNSAT corner in the phase space from the lower left SAT corner. The probability of avoiding load shedding is unity in the SAT domain and it is strictly less than unity in the UNSAT domain. (d) illustrates efficiency of the message passing control algorithm.

strategy achieves a global optimum for a sparse grid. We have shown that redundancy in the grid extends the domain of load-shedding-free operation significantly, and that this message-passing control provides an efficient algorithm for finding respective feasible switching. We will extend this analysis by accounting for additional effects including: (a) AC power flow with both reactive and resistive components, (b) control and graph-structures of larger distribution-level systems available through our collaboration with PNM and the Los Alamos utility, (c) hierarchical dynamical control, (d) fluctuation of the distributed generation provided by consumers, and (e) outages.

## Focus Area 3: Grid Stability

Normally, the grid is well balanced and demand is well under generation capacity. A power-flow solver simulating the grid in this SATISFIABLE (SAT) state finds acceptable generation and transmission capacity to meet consumer demand. Starting from a SAT state and perturbing it by removing generating capabilities, cutting transmission lines, or adjusting consumption loads, one typically arrives at another SAT state. Yet, there are marginal SAT states where such perturbations push the grid into an UNSAT state, where no feasible power-flow solution exists. How can we use controls, such as load shedding or backup generation, to maintain the core of the grid in the SAT state? How does an initial UNSAT condition evolves with or without control? How do we determine what regions of the grid remain operational? To address these questions we will develop *metrics for classification of grid stability and robustness*.

We will study both *structural perturbations*, characterized by generation or transmission infrastructure damage, and *dynamical perturbations* where consumer loads approach capacity. Our target is a metric for stability in the high-dimensional structural and dynamical state space of load demand, generation capacity, and graph connectivity. This metric demarcates the three regions of state space: (a) the stable phase where the system is in a SAT state and small perturbations are locally containable, (b) the marginally stable phase where failure disables a localized region of the grid, and (c) the unstable phase where failure propagates and can affect significant portions of the grid. Development of such classification metrics will have significant impact in ensuring that mitigation strategies are properly employed to facilitate continuous monitoring and self-healing of the grid.

Our metric for the state of the grid will quantify in probabilistic terms the spatio-temporal extent of possible failures. The metric will measure a *distance* from a current SAT state to both the marginal stability boundary [24] and the failure boundary. We will develop heuristic algorithms for calculating efficiently transition probabilities between different states of the grid. The total number of transitions from a given state grows exponentially with the size of the grid and thus, we must focus on a subset of critical transitions. When the system is in a stable state, we will identify its closest marginally stable state. Similarly, when the system is deep inside the marginally stable phase, we will identify the most probable path into the unstable regime. While the transition probabilities into marginally stable and unstable states are very small, the economic costs of the consequent local failures or cascading failures are devastating. To identify such low probability events using direct numerical simulation is very difficult but our sophisticated algorithmic tools [8] are especially well suited for this task.

Mitigation strategies require understanding not only the failure probability but also the actual path to failure. Such a path may be structural (transmission line failure), dynamical (increased consumption) or stem from the combination of the two. We will seek a viable signature detection strategy for anticipating failures using techniques we developed to understand the paths associated with rare events in hydrodynamics [9] and information theory [10]. Specifically, we will adopt our successful *instanton* or optimal fluctuation method to analyze the distance to failure and signature detection. We will identify demand configurations or structural perturbations that can lead to large-scale failure. Our approach is far superior to standard Monte Carlo techniques in its ability to search the exponentially large spaces of graph configurations. We expect that even an incomplete understanding of the critical states will be helpful in anticipating and avoiding failures.

Our signature detection approach will utilize observational data and in particular, large-scale databases documenting the state of the grid before a blackout. We will analyze voltage phase correlations across the grid [25] and we will also investigate topological indicators of correlations using the voltage phase isolines. We will incorporate failure signatures as identified by this correlation analysis into our signature detection algorithm and use the algorithm to process data available through collaboration with ORNL, ANL and NREL. DOE plans to establish grid data centers tasked to store year-by-year grid data over the entire US grid. Petabytes of storage are required if the data is collected event at one-mile space resolution and one-second time resolution. Our signature detection algorithms will guide intelligent and efficient pre-processing, handling, and post-processing of these huge data sets.

We now detail our plans and demonstrate how these approaches can be used to address problems associated with stability of the grid and construction of the aforementioned stability metric.

*Quasi-static model.* As detailed above, we represent the grid as a graph with the nodes representing consumers, generators, and control equipment. The basic equations governing the power flow of electricity expresses the vector of power consumption and generation, $\boldsymbol{P}$, as a quadratic form of the vector of voltages, $\boldsymbol{U}$, where coefficients in the quadratic form are elements of the admittance matrix, $\hat{Y}$, constructed of the impedances of different elements of the grid. All characteristics are complex numbers for AC flows. Solutions of the power flow equations should additionally satisfy the set of operational constraints describing currents, voltage, phase and other graph-specific constraints.

*1. Damage Assessment.* Given damage consisting of $k_0$ removed edges, our goal is to find the largest subgraph for which the power flow equations have a viable solution that satisfies all the operational constraints. The number of cuts $k$ in the resulting configuration is a metric for stability: in the stable state, $k = k_0$, in the marginally stable state, $k - k_0 \ll N$, and in the unstable state, $k - k_0 \propto N$, where $N$ is the total number of edges. Finding $k$ is a difficult mixed (continuous-integer) optimization problem with computational complexity that grows exponentially with system size. We will utilize our expertise in optimization and inference [11] to efficiently find approximate yet accurate solutions. We will expand our studies of the operator response to such failure events [12] to include a network of distributed, autonomous control agents that share local information and coordinate their local responses to find global optimal solution [23].

*2. Worst-case Cascade:* Our next step is to compute the most probable initial damage of size $k_0$ that causes an ultimate damage of size $k$, with $k > k_0$. We will adopt our instanton search algorithm [9, 10]

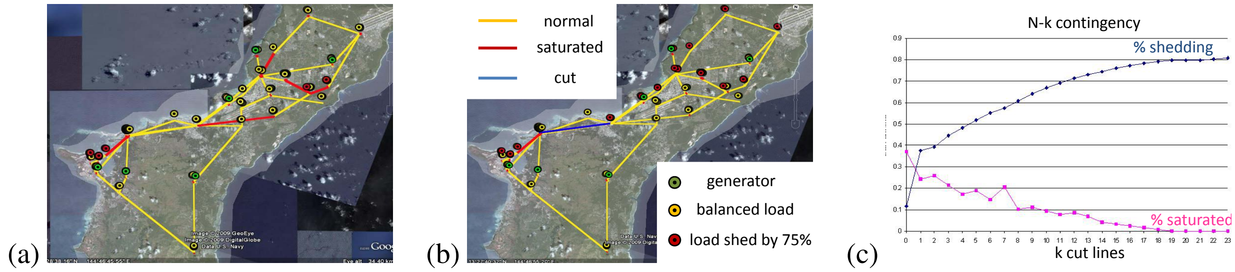



Figure 7: Sample of the Guam transmission grid, consisting of 103 buses (of which 23 are generator buses) and 116 lines. (a) shows a sample original configuration, (b) shows $N-1$ contingency (one line cut) for the original sample with maximum amount of load shed, (c) plots the percent of load shedding and the percent of the number of saturated lines at each value of $k$ for $N-k$ contingency.

to efficiently sample the space of possible failures. The information contained in $k$ and $k_0$ can be used to confine failures in the marginally stable or in the unstable phase. We note that the optimal fluctuation problem can be restated in terms of the network worst-case interdiction contingency [26, 27], thus allowing complementary analysis through application of the related techniques we developed in this area [13]. (See Fig. 7 illustrating our ongoing work [14] on the power grid contingency analysis problem.)

*Dynamic model.* Many aspects of the grid, including generator response to load demands and failure propagation are dynamic in nature. In our quasi-static model a generator is matched to the requested load, but in the dynamic model the mechanical generator power, $P_m$, is a new degree of freedom, which is related to the requested electric power at the generator, $P_e$. The mismatch between the electric and mechanical powers at the generator changes the operational frequency $\omega$, according to $d\omega/dt = (P_m - P_e)/C$, where $C$ is related to inertia characteristics of the generator. At the same time, an active generator control adjusts the mechanical power to electrical characteristics at the generator, such as voltage and frequency, via a feedback loop, $dP_m/dt = -1/R$, with $R(U,\omega)$ a regulation function. The complete dynamical system consists of the generator equations, the power flow equations, which are local in time but globally interrelated according to the grid structure, and the various grid operational constraints. This deterministic set of equations is governed by stochastic inputs corresponding to consumer loads and local grid failure probabilities.

*3. Dynamic Stability:* Our target is robust stability metrics for the grid dynamics. Recently [15], we linearized the underlying system of equations, and derived a linear stability condition for the synchronization of generators (Fig. 8). This eigenvalue analysis offers a convenient operational definition for the distance to failure in the stable and the marginally stable regimes. We will extend this formalism and determine a relation between the network topology and the generator state that maximizes grid stability. We will analyze the feasibility of distributed control schemes that seek to maximize the distance of the operating point to the instability boundary by adaptively performing fast load and generation balancing.

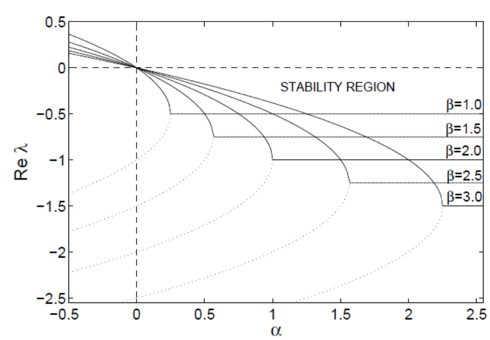



Figure 8: Stability map for a quasi-static model of power grid from [15].

*4. Failure Propagation:* We now apply the dynamics stability metrics to non-stationary and spatio-temporally correlated models of cascading failure. An important preliminary modeling was performed in [28] where a phenomenological stochastic branching model was introduced with rates adjusted to observational data from large cascading blackouts. We will incorporate into this branching process approach effects of power flows and will also model effects of restoration and self-healing. We will employ non-equilibrium statistical mechanics techniques including master equation, giant fluctuations, and instanton analysis [8]. We will provide basic understanding of failure propagation, and also develop algorithms for evaluating the probability and the extent of cascading for critical parts of present day and forecasted US grid. This probabilistic analysis will be used to mitigate damage via control schemes that determine when and where to react to prevent failures.

## III. Institutional Impact

This project leverages laboratory capabilities in information theory, infrastructure analysis, and complex networks for research in a national priority, the smart grid. The team's combined theoretical and applied expertise constitutes a forward looking laboratory capability in analysis of energy systems.

Development of Information Science and Technology tools for smart grids fits naturally within two of the three new incubation centers at Los Alamos. Specifically, smart grid research strengthens the infrastructure analysis priority of the energy security center and the predictive science thrust of the information science and technology center. The proposed research on optimization of renewable placement and the expansion of current laboratory infrastructure analysis tools to include intermittent renewables generation is aligned with the laboratory strategy of targeting problems on the intersection of energy, climate, and infrastructure.

This smart grid effort enables the laboratory to expand its infrastructure planning and analysis programs, currently focused mainly on infrastructure security and sponsored by the Department of Homeland Security, to a broader set of programs in energy infrastructure planning and analysis with the Department of Energy as primary sponsor. The project thereby positions the lab closer to the center of mass in energy research.

## IV. Transition Plan

The smart grid team has been intensely involved in a number of initiatives with substantial prospects for new external programs. First and foremost, the Department of Energy, through a partnership between the Office of Electricity and the Advanced Scientific Computing Research program in the Office of Science plans to establish three major research centers in Grid Analysis. A member of the team represented LANL in the planning meeting in Washington DC and the team is actively engaged with LANL program management and line management in pursuing this important opportunity. Just recently, a member of the team briefed the Secretary of Energy, Steven Chu, during his visit to Los Alamos. Consequent to this briefing, the laboratory is exploring, in consultation with the DOE, the possibility of an energy systems lablet at Los Alamos. The success of these program development efforts requires the laboratory to provide scientific and technical leadership and the research agenda outlined in this proposal is a clear path to this goal.

On the state level, the team is part of the New Mexico Green Grid initiative involving the NM national laboratories (LANL, SNL) and research universities (UNM, NMSU, NMT). Substantial investment by the state with matching federal funds is expected. Our strategy is to couple LANL's modeling and simulation capabilities with our hardware capabilities so that the LANL scope is as broad as possible.

Our partnerships with PNM and the Los Alamos County Utility have been established with a Memoranda of Understanding underway. This collaboration will also strengthen the local utility's case for obtaining funding under the American Recovery and Reinvestment Act.

The team is also engaging university partners from MIT, U of Minnesota, Penn State, U of Wisconsin and U of Vermont. Most of these partners have already visited the lab as part of the comprehensive smart grid seminar series. External grant opportunities include funding from DOE office of science, DTRA, DARPA and NSF.

## V. Budget & Schedule of Deliverables and Milestones

The total budget is 1,650K/1,650K/1,650K for FY10/11/12. The allocation of funds by division is: T-853K/843K/831K, D-400K/416K/433K, CCS-186K/194K/202K and MPA-109K/114K/118K.

| | Grid Design | Grid Control | Grid Stability |
|---|---|---|---|
| FY10 | • Develop comprehensive theory and algorithms for network optimization.<br>• Develop Hybridization & Simulation Approach, first tests on NREL models. | • Local Queuing for PHEV without communications.<br>• Control for distribution level with renewables.<br>• Feeder lines optimization & control. | • Develop classification and metric for different failures.<br>• Study $N-k$ interdiction contingency for the grid.<br>• Develop theory of cascades.<br>• Algorithms for Quasi-Static model. |
| FY11 | • Combine and compare Network Optimization and Hybridization of Optimization approaches.<br>• Develop a set of realistic optimization cost-functions, e.g. accounting for geography. | • Local Queuing for PHEV with communications.<br>• Message-Passing based control across the layers.<br>• Adopt distributed model predictive control technique for power grid. | • Damage control algorithms.<br>• Instantons for signature detection.<br>• Develop algorithms for Dynamical models.<br>• Phase map as a signature. |
| FY12 | • Apply developed algorithms to placement of renewables in the Rocky Mountain Belt.<br>• Account for our stability metric in planning.<br>• Develop/calibrate LANL toolbox for power grid planning. | • Distributed Queuing for PHEV/storage across the grid.<br>• Implement control schemes on test beds.<br>• Incorporate effects of control into planning & analysis of failures. | • Algorithms for cascades, testbed validations.<br>• Signature Detection for peta-scale grid databases.<br>• Develop control for failure prevention & support of the damaged grid. |

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# Overview of Key Participants

Our expertise balances theory including computer science, optimization, machine learning, operations research, information theory, control theory, statistics, and non-equilibrium physics and the applied expertise such as power engineering, energy hardware, energy planning and policy. For additional information, including our publications and preprints, see `http://cnls.lanl.gov/~chertkov/SmarterGrids/`.

## Key Participants' Role:

• Bent, Anghel, Berscheid, Chertkov, Izraelevitz, Johnson, and Toole are responsible for developing a unified set of techniques and algorithms for planning and placement of renewable generation and next generation grid design strategies. Bent, Berscheid and Toole will be working on extending and improving WinDS planning via the new hybrid optimization strategies. Chertkov and Johnson will be developing network optimization techniques and algorithms, Anghel will develop stochastic metric for optimization and Izraelevitz will be consulting on the questions related to multi-objective optimization. Bent will lead this effort.

• Backhaus, Anghel, Ben-Naim, Chertkov, Gupta and Zdeborova are responsible for implementing the smart grid control strategies. Backhaus and Gupta will be working on feeder line optimization for distribution systems. Backhaus, Chertkov and Zdeborova will focus on analysis of SAT-UNSAT transitions and message-passing control of power network with redundancy. Anghel will focus on applying generic distributed model predictive control techniques to smart grids. Chertkov, Ben-Naim, Backhaus, Gupta and Zdeborova will be implementing queuing theory approaches to power grid scheduling and PHEV charging. Gupta will coordinate our collaboration with NM county, LANL utility and PNM on test-beds for the load-balancing and control algorithms developed. Backhaus will lead this effort.

• Chertkov, Anghel, Ben-Naim, Bent, Pan, Santhi, Sinitsyn and Wallstrom will be developing new approaches for grid stability. Chertkov, Ben-Naim, Pan and Sinitsyn will work on developing the rare events and instanton analysis of failures and will employ Monte Carlo verifications. Pan, Chertkov and Santhi will develop $N-k$ contingency approach. Anghel, Ben-Naim and Chertkov will study dynamical models of failures, in particular branching process models. Sinitsyn and Chertkov will be working on non-equilibrium statistical mechanics inspired signature detection techniques. Pan, Bent, Chertkov and Wallstrom will focus on developing new approaches and algorithms for signature detection analysis of peta-scale data sets. Wallstrom will perform statistical and multivariate analysis. Chertkov will lead this effort.

## Brief Bio of Participants:

**Michael Chertkov** (PI, TSM, T-4) received his Ph.D. in theoretical physics in 1996 from Weizmann Institute. He was an R. H. Dicke Fellow at Princeton University, Physics Department and moved to LANL in 1999 as J.R. Oppenheimer Fellow. He joined the Theoretical Division in 2002 as a Staff Member. His area of expertise includes mathematical and statistical physics applied to hydrodynamics, optics, information theory, optimization, control and network sciences. Chertkov has one patent and over 80 publications in refereed journals. He has organized 9 CNLS conferences. Chertkov is leading the "Physics of Algorithms" project, LDRD DR in its last year, which results in many graphical models based methodology and algorithms. As shown in recent transitional studies, with Zdeborova on redundancy and message-passing control for distribution system and with Johnson on network optimization for planning, these algorithms and approaches will be of a significant applied and theoretical value for the smart grid related research. Chertkov's other achievements most relevant to this project are (1) discovery of an explicit relation between the belief propagation algorithm and a loop series representing the complete algorithm on a graph with loops (co-authored with V. Chernyak); (2) development of novel physics inspired instanton approach solving the problem of the error-floor analysis of the coding theory (co-authored with V. Chernyak, M. Stepanov and B. Vasic); (3) development of rare event (instanton) technique for analysis of hydrodynamic turbulence. More info, along with detailed CV, can be found at `http://cnls.lanl.gov/~chertkov`.

**Russell Bent** (Co-PI, TSM, D-4) received his PhD in Computer Science from Brown University in 2005 and joined LANL as a technical staff member that year in the infrastructure analysis group (D-4). He is the capability research and development team leader in D-4. Russell is responsible for development the *IEISS* project that models and simulates energy and communications networks and their inter-relationships, *Logistics*, a project for resource management, planning, and distribution for disasters, and *CEMSA*, a project for designing and coupling inter-operable simulations. Russell's publications include deterministic optimization, optimization under uncertainty, infrastructure modeling and simulation, constraint programming, vehicle routing and scheduling, supply chain, algorithms, and simulation. In the last five years, Russell has published 1 book and over 20 articles in highly respected journals and conferences in artificial intelligence and operations research. Russell has served on the technical program committee for AAAI 2008 and has served as a reviewer for many top journals including Operations Research, Transportation Science, and Journal of Scheduling. He is also a charter member of CPNA (Constraint Programming Society in North America) and the Brown University Optimization Laboratory. A full list of his publications can be found at `http://public.lanl.gov/rbent/`.

**Marian Anghel** (TSM, CCS-3) has received his M.Sc. in Engineering Physics from the University of Bucharest, Romania, in 1985, and his Ph.D. in Physics from the University of Colorado, Boulder, in 1999. He was a postdoctoral fellow at Boston University and at Los Alamos National Laboratory. His research interest include statistical learning and inference algorithms, model reduction and optimal prediction in large scale dynamical systems, and infrastructure modeling and simulations. Relevant to this project, Marian has recently introduced a stochastic model that describes the quasi-static dynamics of an electric power grid under random perturbations and has used this model to analyze the optimal operator response in a damaged or stressed transmission network. Recently, he has worked on the problem of generators synchronization in power grids and has derived a master stability condition applicable to power grids with identical generators. This condition reduces the high dimensional problem to the dimension of a single generator and enables the study of power system stability within a common framework used to investigate the collective behavior and nonlinear phenomena in a wide range of complex systems.

**Scott Backhaus** (TSM, MPA-10) received his Ph.D. in Physics in 1997 from the University of California at Berkeley in the area of macroscopic quantum behavior of superfluid 3He and 4He. He came to Los Alamos in 1998 and was Director's Funded Postdoc from 1998 to 2000, a Reines Postdoctoral Fellow from 2001 to 2003, and a Technical Staff Member from 2003 to the present. During his time at Los Alamos, Backhaus has performed both experimental and theoretical research in the area of thermoacoustics including fundamental topics such as several thermoacoustic streaming instabilities, streaming assisted heat transfer, and acoustic power manipulation. In addition, he has completed several projects with practical applications such as a thermoacoustic-based electric generator for spacecraft and a large-scale thermoacoustic engine for a natural gas liquefaction pilot plant. His work has been recognized with several awards including an R&D 100 award in 1999 and Technology Review's "Top 100 Innovators Under 35" award in 2003.

**Eli Ben-Naim** (DGL, T-4) received his B.Sc. in Physics and Mathematics from the Hebrew University in Jerusalem in 1990, and his Ph.D. in Physics from Boston University in 1994. He was a postdoctoral fellow at the University of Chicago and at Los Alamos National Laboratory. Eli is a fellow of the American Physical Society and of the Institute of Physics. He serves on the editorial board of the Journal of Physics A and previously served on the editorial board of the Physical Review E. He is an expert in non-equilibrium statistical physics an has extensive experience in theoretical analysis and Monte Carlo simulations. Eli's research, relevant to this project, includes extreme event analysis, multi-objective optimization, complex network theory, damage in networks, and population dynamics. Eli was the co-PI and later the PI of the LDRD DR project on statistical physics of complex networks. A detailed CV is available at `http://cnls.lanl.gov/~ebn/`.

**Alan Berscheid** (TSM, D-4) is an Electric Power Engineer and is a project leader in the Energy & Infrastructure Analysis Group. He is responsible for performing system studies on electric power system models to examine the effects of various scenarios including technology implementation and climate change on power systems. He studies how the future electric power network could be configured and optimized under various future load growth scenarios. Alan has also modeled interdependencies amongst various infrastructures including electric power, telecommunications, natural gas, and transportation systems. Alan has also conducted vulnerability studies on critical infrastructure assets and provided options for companies on how to mitigate these vulnerabilities. He is skilled in the use of power flow, power flow reduction, transient stability, geographic information systems, and one-line diagram programs to help with the analysis of infrastructure systems. While with Booz Allen & Hamilton, Alan helped to develop infrastructure assurance plans for several government agencies. Alan received an M.S. in electrical engineering from the University of Minnesota and a B.S. in electrical and electronics engineering from North Dakota State University.

**Rajan Gupta** (Lab Fellow, T-2) is a theoretical physicist whose main research thrust is elementary particle physics. He earned his Ph.D. in Theoretical Physics from The California Institute of Technology in 1982 and joined LANL as a J. Robert Oppenheimer Fellow in 1985. He has published over 125 research papers in prestigious refereed journals in areas of high energy physics, statistical mechanics, high performance computing and computational physics and biology. He is an elected fellow of the American Physical Society and of Los Alamos National Laboratory. He has developed a web based tool to understand global energy systems. He is the lead for modeling and simulations effort on the NM State's Green Grid effort. His focus is on analyzing the dynamics of growth in distributed generation, electric power storage, controls and plug in hybrid cars and their impact on the grid. In particular to develop algorithms for efficient load balancing to reduce spinning reserves of, and dependence on, fossil fuel based power plants while maintaining a reliable and secure supply. A detailed CV is available at `http://t8web.lanl.gov/people/rajan/`.

**David Izraelevitz** (TSM, D-6) received a B.S. (magna cum laude) from Rensselaer Polytechnic Institute in Computer and Systems Engineering and the S.M, and the Ph.D. in Electrical Engineering and Computer Science from Massachusetts Institute of Technology. His areas of research relevant to this project include multi-objective optimization, signal analysis and system dynamics modeling. He has been at LANL since 2005 where he has conducted work in modeling of critical infrastructure vulnerabilities and interrelations as affected by pandemic influenza outbreaks, asymptotic behavior of multi-objective optimization solutions, and statistical approaches to uncertainty modeling. Prior to LANL, he was the lead architect of several tactical analysis software segments for the U.S. Army Corps of Engineers, and developed signal and image analysis algorithms for different national security applications. He is currently chair of the Los Alamos/Northern New Mexico section of the IEEE.

**Jason K. Johnson** (DFPD, T-4) received his Ph.D. ('08) and S.M. ('03) in Electrical Engineering and Computer Science and his S.B ('95) in Physics all from the Massachusetts Institute of Technology, Cambridge MA. He was a member of Technical Staff with Alphatech, Inc., Burlington MA, 1995-2000, where he developed model-based algorithms for estimation problems in multi-target tracking, data fusion and image processing applications. His graduate research focused on developing approximate inference methods for probabilistic graphical models and combinatorial optimization problems. He joined LANL as a postdoctoral research associate in September 2008 and is now a director-funded postdoctoral fellow. His research interests include convex relaxation methods, combinatorial analysis & approximation techniques and multi-scale methods for inference, learning and optimization in graphical models.

**Feng Pan** (TSM, D-6) received his Ph.D. in Operations Research from the University of Texas at Austin in 2005. He is a technical staff member in Risk Analysis and Decision Support Systems Group in Los Alamos National Laboratory. He has been working in the area of nonproliferation and critical infrastructure modeling. He is the lead developer for PATRIOT, a network decision support tool for diagnosing and interdicting global nuclear smuggling. He also worked in the area of telecommunication network modeling and analysis, and he performed simulation and analysis for the telecommunication infrastructure during the 2005 hurricane season. His research interests cover stochastic network interdiction, stochastic programming, and combinatorial optimization models and algorithms. He is the PI of the LDRD-ER "Efficient Interdiction".

**Nandakishore Santhi** (PD, CCS-3) received his Ph.D. in electrical and computer engineering in 2006 from University of California San Diego. After his Ph.D, he moved to LANL in 2006 as a postdoctoral researcher. His area of expertise includes algebraic error correction coding theory, information theory and telecommunication systems theory. He has extensive industry experience having worked with Cypress Semiconductors, Synopsys Inc and AMCC in VLSI system design, 3G wireless communication systems design and optical fiber communication systems respectively. He has authored articles in coding and information theory. He has helped organize through IEEE, international information theory conferences and has served as a reviewer for several international journals and conferences. He is a member of the IEEE Information Theory and Communication societies as well as the SIAM discrete math society.

**Nikolai Sinitsyn** (PD, CCS-3) received his Ph.D. ('04) in Physics from Texas A&M University. He was a postdoctoral fellow at the University of Texas and then a director's funded postdoctoral fellow at LANL. He currently holds an associate postdoctoral position at LANL. His area of expertise includes stochastic networks, controlled stochastic processes, mesoscopic fluctuations and noise in electronic systems. Sinitsyn has about 35 research papers in refereed journals, which have been cited over 1100 times. At LANL, he developed a novel numerical algorithm for fast simulations of stochastic biological processes and developed the theory of current control in stochastic and electrical networks by periodic modulation of parameters. His expertise is particularly valuable for understanding theoretical principles underlying grid failures.

**G. Loren Toole** (TSM, D-4) serves as the Task Lead for several infrastructure projects at Los Alamos. He is responsible for network interdependency and asset prioritization studies delivered to Federal customers including DOE, DHS and DOD. His engineering design, planning and construction experience extends over 30 years, with specialized experience in electric utility planning; renewables project development and design; applying state-of-the-art tools used by electric utilities for generation, transmission and distribution analysis; development and startup of new technical programs supporting infrastructure assurance and homeland security. He has supervised multidisciplinary teams tasked with delivery of analytic products and software. He earned degrees in Electrical Engineering (BS E.E. and MS E.E.) from the Georgia Institute of Technology and serves as an Adjunct Professor, University of Missouri College of Engineering (Columbia).

**Timothy Wallstrom** (TSM, T-4) received his PhD in Physics from Princeton University, and has been at the lab since 1992. Tim has extensive experience in statistical modeling of complex systems. He was one of the codevelopers of QMU, which is used for quantifying uncertainty in nuclear weapons, and has briefed the JASONs on statistical issues related to weapon design. He has worked extensively with oil companies on statistical characterization of oil reservoirs. More recently, he has been working on statistical inference of HIV phylogenetic trees. In addition to the applied work, he has made substantial contributions to foundational issues in Bayesian statistical inference.

**Lenka Zdeborova** (DFPD, T-4) received her Ph.D. in physics in 2008 from the University Paris-Sud in France and from the Charles University in Prague, Czech Republic. She moved to LANL in fall 2008 as a Director's Postdoctoral Fellow. Her area of expertise includes statistical physics of combinatorial optimization problems, message passing algorithms and fundamental properties of glassy systems. Zdeborová has about 15 research papers in refereed journals. Her expertise is fruitful for understanding theoretical principles underlying the structure of a smart grid, as highlighted in a recent study with M. Chertkov on redundancy and message-passing control for distribution system. Her research relevant to this project includes: Analysis of performance of message passing algorithms, computational complexity, and glassy systems.

## External Collaborators:

Utilities: We are partnering with Public Service Company of New Mexico, PNM (W. Ranken, S. Willard) and with the Los Alamos County utility, LAC, (J.E. Arrowsmith, R. De La Torre). LANL has a long standing coordination agreement with LAC on the generation, transmission, and distribution of electricity. The County has expressed a willingness to partner on a smart grid demonstration project and we anticipate formalizing that partnership with a MOU. We will focus on monitoring customer usage via smart metering and management of PHEV in LA county. We will collaborate with PNM on algorithm development for capacitor banks comtrol and on the state-level transmission especially in respect to integration of renewables.

The team is also engaged with the LANL Utility and Infrastructure Division (A. Erickson). Our plan is to use the LANL transmission and distribution systems to calibrate our models and to monitor industrial scale customer usage for the potential for demand control and load balancing to optimize energy usage. The LANL utility infrastructure serves as the tie between the state-level transmission system and the county-wide residential and commercial distribution system. The LANL system has transmission import limitations and the Utility and Infrastructure Division is interested to meet future load demands by optimizing current transmission capacity vice investing in additional transmission capacity.

MIT: Our strategic partnership with LIDS at MIT extends beyond the smart grid project. On smart grids, we plan collaborations with **Munther A. Dahleh**, professor, the associate director of the Laboratory for Information and Decision Systems, on the problems of robust control via distributed agents with local decision capabilities, **David Gamarnik**, associate professor of Operations Research at MIT Sloan School of Management and LIDS, on queuing theory for PHEV management, and **Sanjoy Mitter**, professor, member of the National Academy of Engineering on the theory of stochastic and adaptive control for smart grids. Professors Dahleh, Gamarnik and Mitter have expressed significant interest in the collaboration.

University of Minnesota: **Massoud Amin** holds the Honeywell/H.W. Sweatt Chair at the University of Minnesota and is an internationally recognized leader in the power grid research community. He has strong connections to the electric power research institute (EPRI). He has expressed "delight in collaborating on the efforts in this proposal". **Bruce Wollenberg** is a professor at the University of Minnesota and with Amin one of the original proponents of smart grid (self healing grid). He is the author of the standard textbook on power system engineering, control, and operation. He has indicated a desire to participate in this effort.

University of Wisconsin Madison: **Ian Dobson** is professor of electrical and computer engineering at the University of Wisconsin-Madison, fellow of the IEEE. He has applied nonlinear dynamics and bifurcations to help explain and avoid instabilities of electric power systems and has expressed the "delight to support the proposal and be a university partner" on cascading failure and complex systems aspects of blackout risk.

University of Vermont: **Paul Hines** is an Assistant Professor in the School of Engineering, a member of the adjunct research faculty at the Carnegie Mellon Electricity Industry Center, and a commissioner for the Burlington Electric Department. His research, highlighted recently in Scientific American, focuses on smart grid technology and policy, cascading failures, and decentralized control methods. Dr. Hines is "very excited to work with the Los Alamos team on this important and timely Smart Grid research".

The Pennsylvania State University: **Seth Blumsack** is an Assistant Professor in the Department of Energy and Mineral Engineering. He is also an adjunct researcher with the Carnegie Mellon Electricity Industry Center. His research includes complex networks, smart-grids, and public policies related to the power industry. He has briefed state legislatures and federal policymakers on deregulation, environmental policy and demand response in the utility industry. Dr. Blumsack is currently engaged in smart-grid demonstration projects on the Penn State campus and at the Philadelphia Navy Yard. He is looking forward to "collaborating with researchers at Los Alamos to address the important challenges discussed in the research proposal".