Computational Challenges and Analysis under Increasingly Dynamic and Uncertain Electric Power System Conditions

Future Grid Thrust Area 5 White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Thrust Area 5 White Paper

Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions

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PSERC Publication 12-15

May 2012

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Power Systems Engineering Research Center

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Acknowledgements

This paper was developed as part of "The Future Grid to Enable Sustainable Energy Systems: An Initiative of the Power Systems Engineering Research Center (PSERC)." This project is funded by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability. More information about the Future Grid Initiative is available at the PSERC website, www.pserc.org.

Executive Summary

The future grid will include millions of human and artificial decision-makers. It will be characterized by increased uncertainty, ubiquitous access to information, and more ambitious economic, reliability, and sustainability operational and planning objectives. Designing and building larger and faster computers and faster communications will not be sufficient to solve the computational problems of the future grid. New computational methods must be developed based on superior control architectures and new algorithms, and deeper understanding of emerging relevant phenomena. These methods must be able to handle problems of growing complexity accounting for uncertain conditions, the effect of non-dispatchable resources, and customer participation. The required fundamental advances in computational systems arise in the areas of architecture, control and optimization algorithms, data management, modeling, and security. Thrust Area 5 is addressing the following challenges:

1. **Decision-Making Framework for the Future Grid**: The task is developing a broad decision-making framework that acknowledges the emergence of new actors in the grid: microgrids, aggregators, buildings, homes, etc. These new actors are abstracted using a boundary object (prosumer) which is an economically motivated entity that pursues its own energy objectives, and provides consumption, production and storage services. The proposed framework covers the relevant spatial and temporal scales, addresses decision complexity, and acknowledges meta-decision makers at the level of community of actors and government institutions. When fully developed, the framework will provide a reference that enables the future grid objectives to be met by design.

2. **Computational Issues of Optimization for Planning**: Long term planning has always been complicated by uncertainty but the levels, dimensionality and volatility associated with uncertainties that affect generation expansion planning, are increasing. In this research, we are reducing the number of possible future scenario paths that must be considered by focusing on how they affect the planning decisions to be made immediately. We are investigating how competition among suppliers combines with transmission constraints and demand response to influence their separate investment decisions.

3. **Hierarchical Probabilistic Coordination and Optimization of Distributed Energy Resources (DER) and Smart Appliances**: This task is developing a three-level hierarchical stochastic optimization methodology in real time around the physical separation of power systems into feeders, substations, and power grid. A new approach for monitoring and controlling the plethora of small resources via a coordinated (hierarchical) optimization and control approach is being developed.

4. **Real-Time PMU–Based Tools for Monitoring Operational Reliability**: PMUs have been acknowledged as an enabling technology for transforming real-time power system operations. Despite this potential, the truth is their utilization in real-time operational reliability monitoring has been limited. This task is developing real-time PMU-based tools for helping operators with operational reliability issues: a) System loadability condition monitoring, b) Transient stability analysis, and c) Real-time line model and equivalent parameter updating.

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1 Introduction

Computational methods and information systems have been at the center of secure and economic planning and operation of electric power systems for several decades. Today, transformational forces such as: renewable energy, distributed resources, energy storage, massive sensing, customer owned resources, environmental concerns and mandates, etc., pose numerous and much more difficult computational challenges. The addition of sustainability objectives to the traditional goals of grid economy and reliability has resulted in growing uncertainty and complexity, and is likely to render a significant portion of the existing computational methods and information systems obsolete. Thrust Area 5 of this project investigates these computational challenges.

The new decision-making tools needed in operations and planning must be based on computational methods that are capable of handling problems of growing complexity and that account for uncertain conditions, the effect of non-dispatchable resources, and customer participation. On the other hand, the availability of massive and more detailed data from phasor measurement units (PMUs), intelligent electronic devices (IEDs), and advanced metering infrastructure (AMI) provides great opportunities for improved grid planning, operation and control, but ways must be found to aggregate, organize, and keep this data secure so that it can be leveraged to upgrade, extend, and replace existing modeling, computation, control, and decision making tools. The role of computational systems in the future grid is illustrated in Figure 1, which highlights the following areas: an emerging grid, massive new data, advanced computation, and decision-making (automatic or human).

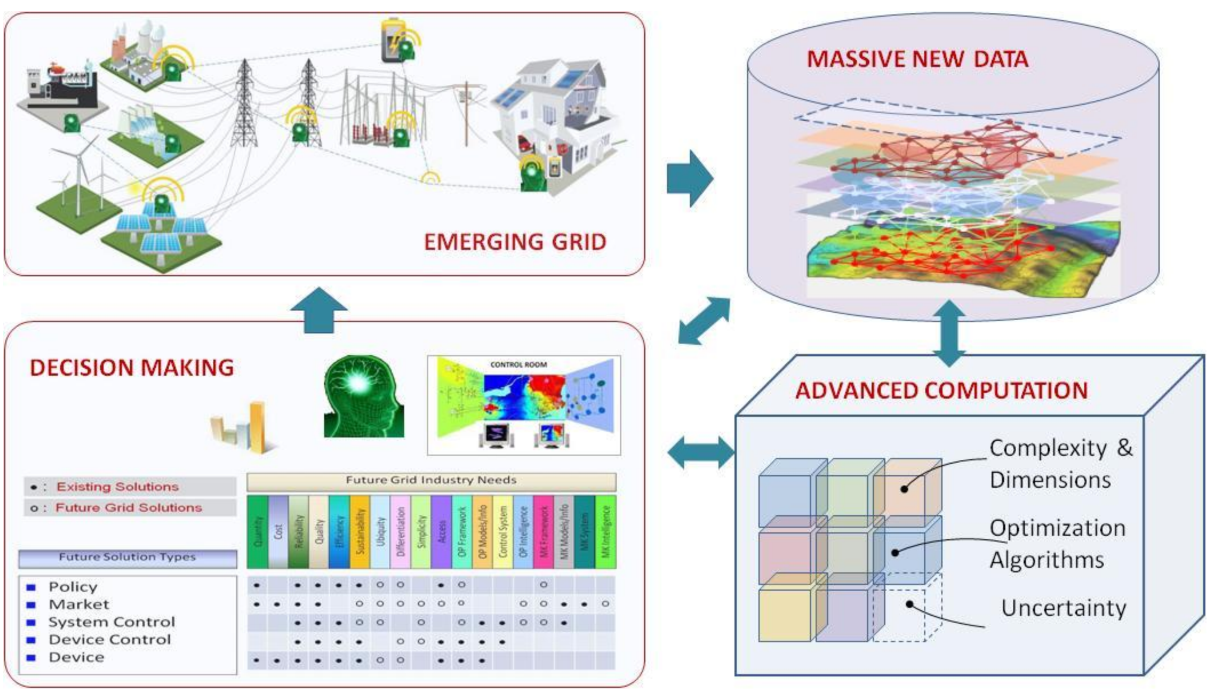

Figure 1: Computational Systems in the Future Grid

Designing and building larger and faster computers and faster communications will not be sufficient to solve the computational problems of the future electricity grid. The fundamental advances are in the areas of control and optimization algorithms, especially distributed control and stochastic optimization, data management, modeling, architecture and security. The following sections address some of these key research issues. Thrust Area 5 focuses on the following key computational challenges, which if addressed, will provide significant input for strategic technology development and policy:

1. **Decision-Making Framework for the Future Grid**: This task is developing a broad decision-making framework for the future grid that a) ensures that the goals of the future grid can be met, b) covers all relevant spatial and temporal scales, c) addresses decision complexity, and d) identifies the gaps and technological needs for the industry transition.
2. **Computational Issues of Optimization for Planning**: This task is developing improved computational methods for long-term resource planning under uncertainty with efforts to: a) further develop, implement and test a method to reduce the number of scenarios considered in stochastic programming when implemented with a rolling time horizon, and b) solve multiple variations of a bi-level optimization problem with uncertainty.
3. **Hierarchical Probabilistic Coordination and Optimization of Distributed Energy Resources (DER) and Smart Appliances**: This task is developing a three-level hierarchical stochastic optimization methodology in real time around the physical separation of power systems into feeders, substations, and power grid. It addresses technology aspects and quantifies expected benefits.
4. **Real-Time PMU–Based Tools for Monitoring Operational Reliability**: This task is developing real-time PMU-based tools for helping operators with operational reliability issues: a) System loadability condition monitoring, b) Transient stability analysis, and c) Real-time line model and equivalent parameter updating.

2 The Opportunity and the Challenge

2.1 Decision Making Framework for the Future Grid

Decision-making either automated or through humans, is at the core of the success of any enterprise or industry. Because the future grid has new goals, more stringent control requirements, and increased uncertainty and complexity, a significant portion of the existing decision-making processes in the industry are already or will soon become obsolete. Contrary to the traditional grid components, all the smart devices, engineering subsystems, and economic agents present in emerging grids will make decisions in order to achieve their individual objectives and the overall goals of the grid. Thus, the secure evolution of the grid and its ability to realize its objectives depend on the decision-making capabilities embedded in the grid and the ability to address questions such as: can operational problems be identified and solved, are the relevant models accurate [1], are the analytical tools powerful enough, can all critical decisions be made in time and satisfactorily, how far ahead can stakeholders plan. Among the future grid challenges in decision-making are:

a) Emerging system behavior and context relevance appears at new *temporal scales* (PMU, wind variability, etc.) [2], and at new *spatial scales* (wide-area, microgrids, aggregator, building, and homes). Therefore, models of diverse granularity are required from interconnections to management of ubiquitous personal energy devices.

b) Enhanced processing of *massive data*, including filtering, mining and learning.

c) Shift from instantaneous optimization (e.g., SCOPF) to complex scheduling due to demand shift, DER temporal variability, electric vehicles, and storage [3].

d) Schemes to enable sustainability objectives through demand mechanisms [4].

e) Considerations of consumer behavior in energy utilization and energy efficiency.

2.2 Computational Issues of Optimization for Planning

As integration of renewable energy increases and demand becomes more responsive to price, long-term resource planning problem formulations must incorporate increasing levels of uncertainty. In stochastic programming models, uncertainties are expressed in terms of probabilistic scenarios, and decisions are divided into two sets. First stage investment decisions must be committed to before the scenario realization is known, while second- or later-stage operational decisions can take recourse depending on which scenario occurs. A full representation of multidimensional uncertainty results in a large number of scenarios and computational intractability. At the same time, considering the market implications of planning decisions requires a bi-level structure where planning decisions in the upper level anticipate market reactions in a lower level equilibrium among market participants. Such problems also pose computational challenges.

2.3 Hierarchical Probabilistic Coordination and Optimization of DERs and Smart Appliances

Renewables and other DER including storage, smart appliances, PHEVs with V2G capability, microgrids, etc., offer the unique opportunity to transform the distribution system into an active and controllable resource with dramatic impact on system economics, primary energy source utilization (including shifts in fuel usage from petroleum to nuclear, natural gas, etc. and associated shifts in greenhouse gas emissions), and ancillary services and improvements for system security. It is clear that these benefits cannot be realized without the coordinated and optimized utilization of these resources. The anticipated large number of these small resources, their uncertainty and mobility (PHEVs) creates a huge and challenging probabilistic coordination and optimization problem. The overall challenge is to develop a hierarchical stochastic optimization method and a supporting infrastructure to capture the potential benefits by:

- **a)** Levelizing total load, which results in utilization of most efficient units, shifts to environmentally favorable primary fuels, and GHG emission reduction,
- **b)** Minimize losses substantially (i.e. 30%) since the largest part occurs in distribution,
- **c)** Provide ancillary services - power electronic interfaces provide a variety of controls including voltage/reactive power control, and
- **d)** Maximize distribution system reliability by providing real-time information of outages, reconfiguration, etc., and to the grid, by assisting at times of need.

2.4 Real-Time PMU-Based Tools for Monitoring Operational Reliability

This task is developing real-time PMU-based tools to support operator actions that ensure high grid reliability. We address specific challenges: i) System loadability condition monitoring and ii) Transient stability analysis. A key feature of this research is the use of PMU data along with limited knowledge the system topology and/or system parameters.

Power System Loadability is related to voltage collapse and small-signal stability analysis. Our initial hypothesis is that it is possible to infer the system loadability condition from phasor information across certain transmission lines collected in real-time by PMUs, without relying on having an accurate model of the system. This model-less operational reliability assessment method relies on calculating the *angle across the system* as seen by every monitored line. Visualization displays and real PMU data processing and analysis tools are being pursued with MISO through a CERTS project in progress.

Online Transient Stability Analysis is conducted by performing time-domain simulation of “what if” scenarios. This project is investigating the possibility of inferring transient stability properties from phasor information without having to rely on a detailed model of the system dynamics. Similar to the line-loadability condition monitoring, the premise is that for every monitored line, phasor information can be used to estimate two-machine system *dynamic equivalent models* as seen from both ends of the line.

3 The Research Issues

Designing and building larger and faster computers and faster communications will not be sufficient to solve the computational problems of the future electricity grid. The fundamental advances are in the areas of control and optimization algorithms, data management, modeling, architecture and security. The following sections address some of these key research issues.

3.1 Decision Making Framework for the Future Grid

The transformation of the electricity industry is characterized by increased uncertainty and complexity. The existing decision and business processes must evolve to ensure that they leverage massive data, advanced computation methods, and analytical tools, and that the future grid can actually meet its desired objectives, while ensuring a safe industry transition. Task 1 of this Thrust Area addresses questions such as: how existing decision processes will be affected, what new decisions are to be made, who will make them and how, what decisions need to be automated, how the technologies currently being deployed support new decision processes, and whether there is a unified emerging paradigm for decision making in the future industry.

Central to the decision-making framework is the emerging concept of *prosumers*: economically motivated entities (homes, buildings, microgrids, etc.) who not only consume, but can also produce or store energy, and that are equipped with enabling technologies that allows them to optimize and become strategic in the decision-making process. Prosumers also exhibit a range of values, including what they stand for in terms of social values, and what they believe is appropriate for the society. This is particularly relevant at the individual level when addressing sustainability response effects. Various models of qualitative analysis frameworks that encompass not only marketed or assigned values but also held values have been identified. They all include social discussion between the various decision making entities to formally or informally evaluate these non-monetized values. This pluralistic and multi-scale approach of decision making allows for not being locked into Pareto optimal states that may not be socially desirable. In order to consider held values in the model currently developed, the idea of a possible cooperation between a set of decision making entities should be introduced in the model.

We propose to consider a new descriptive framework based on the concept of *prosumer* that accurately reflects these functional grid ongoing changes. The prosumer concept represents a new type of *boundary object*. Prosumers have their own objectives associated with the control and utilization of electricity. These objectives are aligned with the goals and preferences of their owners. A boundary object using prosumers as constituent entities is adapted for multi-scale modeling: any player in today's electricity grid can be modeled as a prosumer. The prosumer abstraction is also adapted to the future evolutions of the grid where each player is likely to gain access to additional functions. Therefore, a boundary object based on prosumer interactions can be proposed for the future grid.

The *community of decision makers* interacting with this boundary object is made of prosumer owners –who are not only decision makers but also grid users, experts and elected officials. Because prosumer owners may define their objectives based on a multi-scalar set of values (including economic, reliability, or sustainability aspects), these objective functions are best represented by vectors $\vec{u}_k^p$ lying in multi-dimensional spaces, and may vary over time in order to adapt to a changing environment. This approach using multi-dimensional objective spaces relates to the work that has been done in the area of multiple-criteria decision making, also referred to as multiple-attribute or multi-objective decision making. At the system level, the various decision makers also set objectives, but for the entire grid. These objectives can also be expressed using a vector function $\vec{u}^g$ that varies over time as the discussants gain a shared understanding about what the future grid should look like, and how their environment is changing. An important distinction between the prosumer and system levels lies in the types of values that inspire the formulation of the various objectives pursued. Citizen values play an important role in the way decision makers set their objectives at the system level. In contrast, consumer values are likely to be dominant at the prosumer level.

The concepts of *rules* and *mechanisms* defined in Hierarchy Theory can be used to characterize the boundary object and its constitutive entities. The community of decision makers sets rules that constrain both the way prosumers buy and sell energy services on the electricity markets, and the way their internal functions – to consume, produce, store and transport electricity – are implemented. On their side, the community of prosumer owners set mechanisms that allow them to pursue their objectives within the constraints set at the system level. For each level of the hierarchy (prosumer-level and system-level), various levels of decision can be identified as shown in Figure 2. Three meta-stages of decisions can be defined. First, agreeing on a boundary object; second, deciding on an objective function, either $\vec{u}_k^p$ for a prosumer k, or $\vec{u}^g$ at the grid level; third, defining which type of information, and which type of intelligence (or computational capabilities) will be needed to pursue this objective.

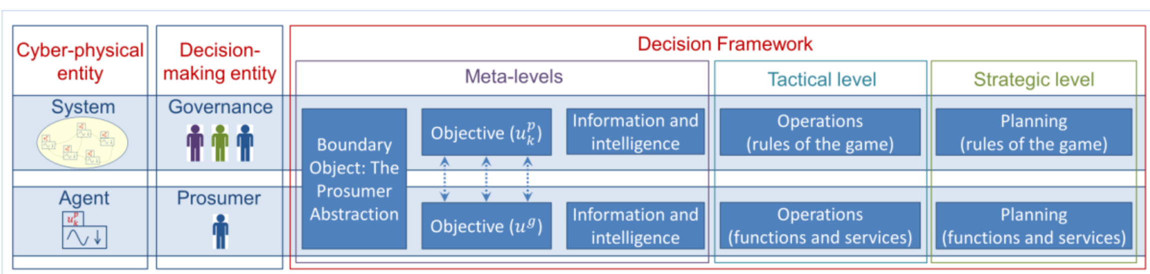

Figure 2: Principal Actors in the Decision Making Framework

In addition to these three meta-stages there are two other decision levels associated with the temporal scale of the decisions. The first stage is the tactical level (or operational level) which consists of making the most of the resources currently available. For prosumers, this tactical stage consists of making the most of the functions and services currently available. At the electricity grid level, the tactical stage consists of making the most of the current rules – policies and/or regulations – in order to get closer to the objectives set by the community of decision makers. The second additional decision stage is the strategic level (or planning stage) which consists of deciding which new functions or mechanisms (prosumer perspective), or which new rules (system perspective) will be needed in the future to better adapt to the changing environment and get closer to the objectives pursued.

In addition to the temporal aspects related to the planning and operation of the various energy functions and services, the prosumer owners are also to decide which level of cooperation they want to pursue. This cooperative dimension ranges from going completely off grid (pure optimization), to pure competitive strategies (Nash equilibrium), to engaging in cooperation with other prosumers in order to move closer to Pareto optima, or to move along Pareto frontiers in order to maintain the level of energy services provided by the electricity grid, but distribute these services differently across the prosumers. This cooperative behavior can be exhibited during grid event conditions, such as grid attack or recovery. The framework hence would support desirable use cases associated with ultra-reliability and resilience of the grid.

3.2 Computational Issues of Optimization for Planning

This task focuses on generation expansion planning (GEP). To incorporate uncertainty in the form of scenarios for a stochastic programming model, the first step is to formulate stochastic models for uncertain variables such as future loads and fuel prices, which are continuous quantities. Next, scenario trees that consist of discrete nodes, each representing a possible combination of values of the uncertain quantities at a future point in time along with conditional branching probabilities, must be formed to approximate possible evolution paths in the future. With even a very small number of branches from each node, over a multi-period time horizon the resulting tree can become very large. Because the outcomes of a candidate expansion plan must be simulated explicitly or implicitly for every path from the root of the tree to a leaf node at the end of the time horizon, the computational task can become intractable. Thus, the main research issue is to derive a smaller set of scenarios that well represent the impacts of uncertain variables on the optimal investment decisions.

The activity in this task is to further develop, implement and test a method to reduce the number of scenarios considered in a stochastic programming model of GEP. In our two-stage model, the first stage represents decisions to invest in new capacity of various types of generating units over the planning horizon and the second stage represents energy production by existing and new units in each period. In previous research, a scenario reduction method termed Forward Selection in Wait-and-See Clusters (FSWC) was developed for medium-term fuel and generation planning problems [5]. A deterministic "wait-and-see" sub-problem problem is solved for each path in the scenario tree and the first stage decisions are recorded. The scenario paths are clustered according to similarity of the first-stage decisions obtained. Then a widely used forward selection heuristic [6] is applied to select one scenario from each cluster. Finally, the two-stage problem is solved using the reduced scenario set. The clustering procedure must be customized for each application. In this project, we are investigating the best subset of investment variables or their transformations upon which to cluster the scenarios. Computational tests are performed to compare this method against forward selection alone based on computation time and similarity of the first-stage decisions obtained [7, 8]. Success in this activity will enable the inclusion of more sources of uncertainty and permit more detailed simulations over long time horizons.

The model described above represents investment decisions made by a single utility to serve captive load or by a central authority if it were able to dictate expansion decisions for a whole region. However, in restructured environments the expansion decisions are made by profit-seeking generating companies (gencos) who can sell energy in wholesale markets. The increasing potential for demand to respond to price in these markets requires that gencos anticipate competing supply offers, demand bids of buyers, and the system operator's market-clearing decisions. All of these can be complicated by transmission congestion. To incorporate the effects of market behaviors on genco investment decisions, the main research goal is to formulate and solve a tractable version of a bi-level equilibrium game involving separate generation expansion planning decisions by multiple gencos in the upper level and a wholesale electricity market equilibrium in the lower level. The market model includes delivery decisions of fuel suppliers, market-clearing decisions of the system operator and generation quantity decisions of the gencos in acting in Cournot competition. Each genco's upper-level problem can be reformulated as a mathematical program with equilibrium constraints (MPEC) by replacing the lower level optimization problems with their equivalent first-order optimality conditions. In each genco's problem, the other gencos' capacity expansion decisions are considered as fixed parameters. One way to find the equilibrium solution is by diagonalization, that is, to iteratively solve each genco's problem by fixing the other gencos' expansion decisions to their current optimal solutions. If this process converges, the limiting set of optimal decisions by all gencos will represent a Nash equilibrium. The diagonalization process is illustrated in Figure 3.

Several research issues result from the notorious difficulty of solving MPECs and their combination, equilibrium problems with equilibrium constraints (EPECs). There may be no equilibrium or several, and the diagonalization process may fail to converge. An equilibrium in the lower-level problem does exist [9]. Current research efforts are aimed at finding tractable reformulations of the lower-level optimality conditions and solving the MPECs as either mathematical programs with complementarity constraints or nonlinear programs. If successful, the results will provide understanding into how demand response, transmission constraints (or their relief) and market incentives will influence planning by gencos.

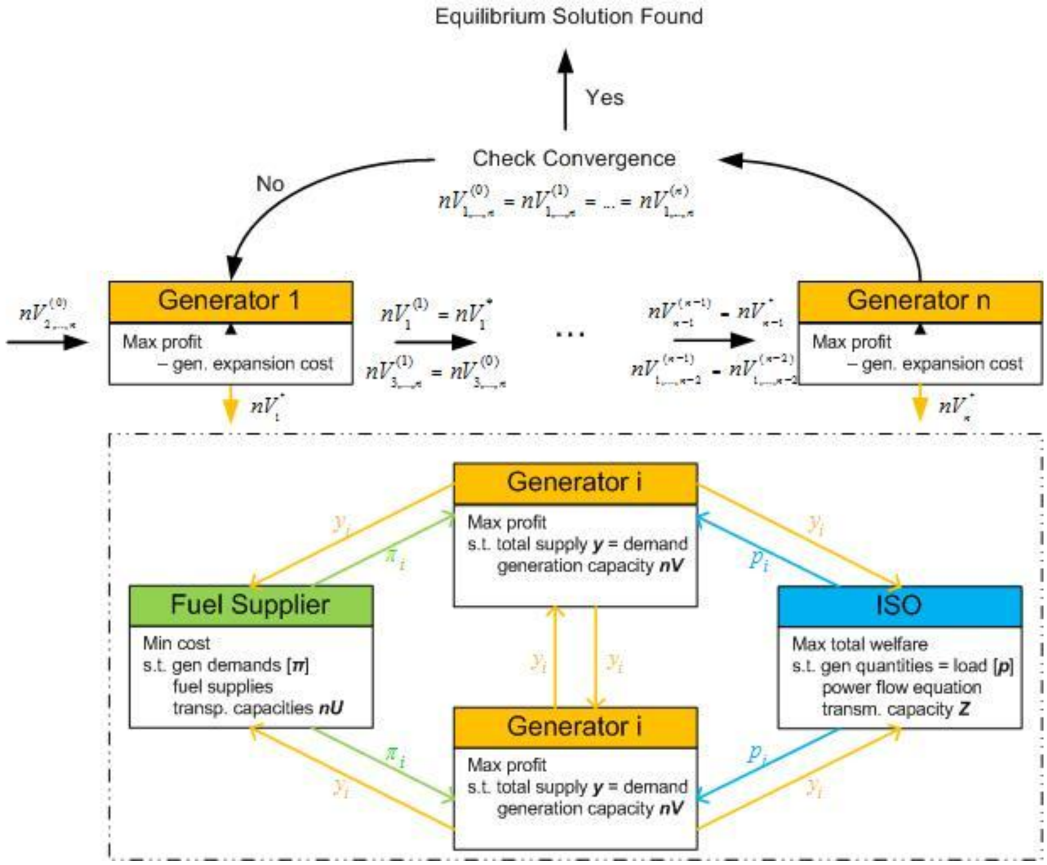

Figure 3: Solving the Equilibrium Bilevel Program

3.3 Hierarchical Probabilistic Coordination and Optimization of DERs and Smart Appliances

The plethora of energy renewable technologies, the advances in end user equipment, and the controllability of such equipment (smart appliances) as well as new technologies such as EV, PHEV, etc. have changed the landscape of energy systems. The new paradigm offers great possibilities for cost reductions and environmental benefits [10-14]. Maximum benefits, monetary and environmental can be achieved with proper coordination of resources and consumers. The control strategies towards coordination and realization of benefits can be mainly divided into three categories (a) distributed control that can be enabled with price signals, incentives and other financial tools, (b) coordinated centralized control, and (c) hybrid control where some resources using distributed control and some centralized. Distributed control implies that each individual Distributed Energy Resource (DER) and smart appliance in the distribution system has its own independent control scheme and there is no communication or coordination among the devices. A typical example of an independent local control scheme is a priced based demand response scheme for the purpose of peak load reduction of the distribution system. Specifically, real time price signals are sent to the customer and the customer owned smart appliances and resources or the customer himself will respond to the price signals accordingly (e.g. turn on or off devices, tune up the temperature settings of the air conditioners, etc.). The major advantage of such control schemes is simplicity. However, the major drawback is that they may lead to unexpected results such as shifting of the peak load instead of reduction and possible higher peak values.

A centralized control strategy implies a system level optimization and coordination architecture that is applied to the distribution system. It is obvious that a coordinated utilization of the available resources in the distribution grid will lead to an optimized grid operation with significant impact in (a) system operation (reduced losses and peak load reduction), (b) system reliability and protection and (c) system economics. However there are major challenges in the implementation of such a scheme. First of all, the anticipated massive number of the DERs and the uncertainties that they introduce (availability, mobility etc.) lead to a large scale challenging problem. In addition this scheme requires the installation of an infrastructure that will support it, which in general is expected to be a combination of tools including metering and communications infrastructure as well as processing of data for real time modeling of the system and model based controls. The implementation of such an infrastructure cannot be accomplished without the necessary investments from the involved parties (utilities, government, industry, etc.).

In this work a hierarchical stochastic optimization method is proposed along with a supporting infrastructure that coordinates the operation of non-dispatchable resources and other resources including storage, smart appliances, and PHEVs with the ultimate goal being: a) improved system operation and economics resulting from peak load reduction and loss minimization b) improved environmental impact from using environmentally friendly sources with less greenhouse emissions c) improved operational security from ancillary services and controls provided by the power electronic interfaced devices and d) maximization of the value of renewables.

To achieve these goals, a three-level hierarchical stochastic optimization methodology that is implemented in real time is proposed. The hierarchical method has three levels: (a) distribution feeder optimization, (b) substation level optimization, and (c) system optimization. Key element to the proposed approach is the interface variables (directives) that are set by the higher optimization levels. Tentatively, the directives are defined to be a) total stored energy in all feeder resources during the planning period b) minimum reserve and spinning reserve margin in all feeder resources within the planning period and c) VAR resources.

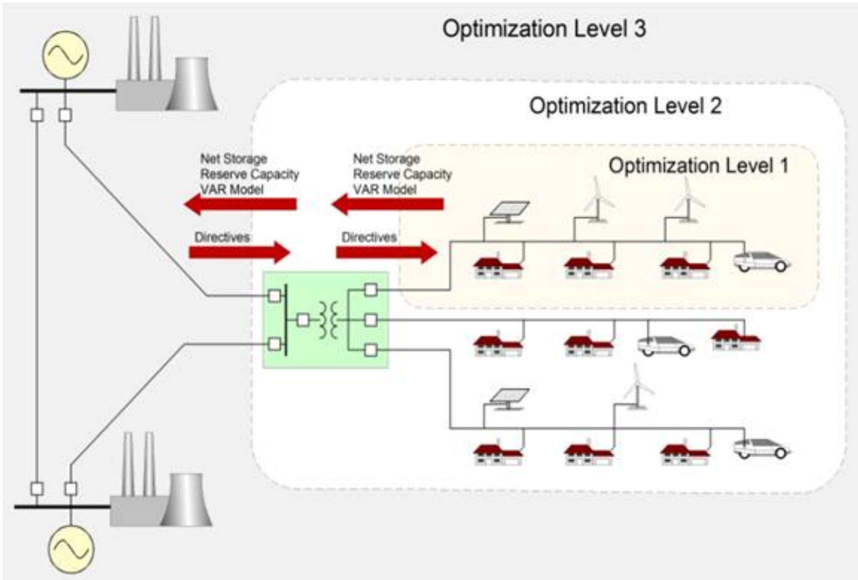

Figure 4: Hierarchical Optimization Model

At the lowest level (feeder optimization) the problem is formulated as a quadratic optimization problem that is solved via barrier methods. The objective function is the minimization of the total operating cost of the feeder over the planning period (typically one day). This objective will guide the solution towards levelizing the apparent load at the start of the feeder and minimize losses because the cost of using electricity from the main grid (substation) will have higher cost during peak hours. The formulation of the problem will also guide the solution towards minimizing the operating losses. At the higher levels the problem is formulated as a stochastic dynamic programming problem. It depends on the aggregate model of the feeders it serves provided from the feeder optimization in terms of the interface variables/directives. The overall approach is illustrated in the figure above that shows pictorially the interfaces between the three levels of the hierarchical optimization method. The full formulation of the problem is provided in the full report.

A business case study has been performed in order to compare the benefits resulting from the aforementioned resources (a) with uncoordinated operation and (b) with the proposed coordination and optimization. Under each scenario, the "apparent load" to the bulk power grid generating system is determined (actual loads, minus distributed generation, plus storage loads, etc.), and the resulting system is simulated with a probabilistic production cost analysis tool to determine (a) expected operating cost, (b) expected fuel utilization and (c) expected pollutants.

Preliminary results have been generated by applying the proposed algorithm on a utility scale test system with 22 GW capacity, 40 generator units (coal, nuclear, oil, natural gas) and 6.6% of penetration of DERs and storage devices. The results indicate that there are significant cost savings (reduced total and average production cost), reliability improvement of the grid (decrease of Loss of Load Probability (LOLP) and Unserviced Energy) and reduction in the pollutants emissions resulting from the proposed optimization scheme. A significant peak load reduction is also achieved.

One byproduct of the optimization scheme is the reduced cycling of dispatchable generating units. Preliminary results using the system mentioned above indicate that while the objective of the optimization is the minimization of the overall operating cost of the system, the optimal solution also reduces the number of cycles and the average MW variation per cycle of the thermal dispatchable units, thus increasing the reliability of the system.

Another byproduct of the optimization scheme is the improvement of the capacity credit of non-dispatchable units, such as wind or solar. In particular, the probabilistic production costing methodology is used to evaluate the reliability of a system, in terms of reliability indices such as LOLP and Unserviced Energy. Then the "capacity credit" for each of the non-dispatchable generation can be computed, defined as the capacity of a dispatchable unit with a specific forced outage rate (FOR) that will provide exactly the same reliability improvement (measured with LOLP) as the wind farm capacity. Note that the capacity credit of non-dispatchable generation is defined in terms of a specific FOR. Numerical experiments that have been performed demonstrate the improvement in the capacity credit of non-dispatchable units upon the application of the proposed hierarchical scheme.

3.4 Real-Time PMU-Based Tools for Monitoring

Power system operational reliability analysis is typically concerned with three phenomena—closeness to voltage limit, current limit, and instability bounds. In [15], St. Clair introduced a concept, based upon practical considerations and experience, to express indirectly these reliability constraints in terms of only line power flows. The idea, captured by a pair of curves, was to describe the maximum allowable power flow for transmission lines of any length. The basic concept relied on the notions that short lines are thermal limited, whereas lines approaching 300 miles in length are limited to 1.0 SIL (Surge Impedance Loading) by system stability considerations.

In the single lossless line model with fixed voltage magnitudes at both ends, the steady-state stability limit occurs at a 90 degree voltage angle separation across the line. When the angle separation is around 45 degree, the loading is about 70 % of the maximum (leaving a 30 % margin). This rule-of-thumb used in the industry played a key role in an analytical procedure for constructing the St. Clair curves proposed by Gutman et al. in their seminal papers [16, 17]. The beauty of this procedure lies in the use of Thevenin equivalents at each end of the line, see Fig. 5. If the equivalents can be obtained from PMU data, then these measures can be calculated without any dependence on network models or topology. Furthermore, it is possible to conduct all necessary computations on the PMU processor without a need to push the data to a centralized location. While the nonlinearities of constant power constraints raise questions about the theoretical validity of these equivalents, their simplicity offers enough incentive to consider using this same concept with Phasor Measurement Units (PMUs) to provide real-time reliability measures for situational awareness. Thus, a key objective of this research is to investigate the theoretical basis for relying on estimation using simple model-less angle measurements, which to our knowledge, have not been rigorously pursued.

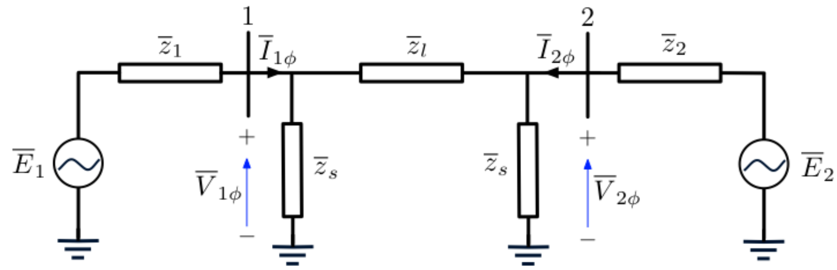

Figure 5: Line Loadability Analysis Model

The use of equivalents of this type has stimulated discussion about the existence of parallel flows that exist in the network around the embedded line, see Fig. 6. Indeed, this was discussed in paper [17]. While, it is possible to reduce the network in Fig. 6 to a network of the form in Fig. 5 by using circuit analysis tools, in particular Miller's theorem (see, e.g., [18]), again due to the nonlinearities in the power flow, it is not clear that the resulting model accurately captures the phenomena of interest.

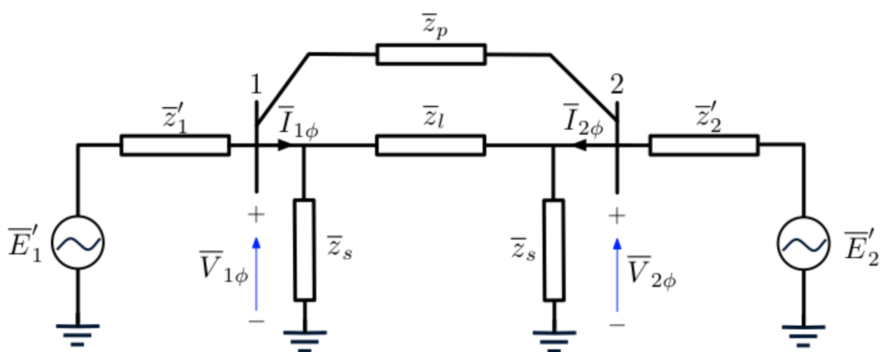

Figure 6: Line Loadability Analysis Model with Parallel Path

Another aspect of the use of PMUs for operational reliability monitoring that has brought significant attention in the community deals with transient (see, e.g., [19, 20]) and voltage stability (see, e.g., [21, 22]). Similar to the line loadability condition monitoring, the premise is that for every monitored line, phasor information can be used to estimate two-machine system *dynamic equivalent models* as seen from both ends of the line. In this regard, since the system is continuously evolving, so are the phasor measurements. Thus, once a structure of the dynamic equivalents is chosen (the simplest realization is the classical machine model) it is possible to use the dynamically evolving phasor measurements to infer the parameters of the dynamic equivalents. With such a simplified model, it is possible to do on-line transient stability analysis after faults in all monitored lines, but as with line loadability, the validity of such models have not been rigorously established, except for radial systems.

While the working hypothesis is that these Thevenin-based models might be sufficient to capture the phenomena of interest, a result of this work will be to indeed validate this hypothesis or show where and why the reduced models break. In this regard, it is important to note that operational reliability modeling based on the ideas above assumes that no information is known about the system topology and/or parameters. This is appealing due to the simplicity of the computations involved but the accuracy of the method is questionable. On the other side of the spectrum, if the system topology and/or parameters are completely known and there are enough PMU measurements to infer the system state in real time, it is possible to obtain a very accurate picture of the system operational reliability. Thus, it is obvious that there is a tradeoff between the available information in terms of system-state measurements, topology and parameters, and the accuracy of the results. In this scenario, it might be the case that there are other types of reduced-order models that take into account partial knowledge of the system topology and/or parameters and capture, with enough accuracy, the phenomena of interest.

4 The Future Grid

The future grid will include millions of human and artificial decision-makers. Decisions need to be coordinated in such a way that while the various actors can achieve their individual objectives, the system continues to operate reliability, economically and in a sustainable manner. Developing a formal decision-making architecture that is scalable to millions of actors would enable the future grid to achieving its ultimate objectives.

The future grid will integrate a plethora of energy renewable technologies, smart end user equipment (smart appliances, user resources, etc.) as well as new technologies such as EV, PHEV, etc. As a result, the future grid will be a more dynamic, more controllable and more complex system. Such a system is capable of optimizing its operation if properly controlled or it has the capability to create times of extreme stress and possible collapse if left uncontrolled due the extreme variability of these resources. On one hand, controlling and coordinating the plethora of the distributed and controllable resources will create enormous financial and environmental benefits for the overall system. On the other hand this ability to control and coordinate these resources will require an expensive infrastructure and development of new coordination technologies. It is believed that the benefits will outweigh the cost of the required infrastructure. The debate of what scheme will be the most workable will continue for many years; open market approaches that will work via pricing and incentive signals or coordinated control and coordination that may require the cooperation of the majority of the customers. The workable approaches will definitely result in a system that will take advantage of the increased controllability for the purpose of: (a) minimizing overall cost, (b) decrease environmental impact, (c) improve reliability and (d) decrease reserve requirements. The proposed hierarchical optimization approach has the objective of evaluating the benefits and costs of a coordinated control of the future grid with the large number of small resources that will definitely have large uncertainties associated with them as well as their control will require the cooperation between the future grid and the customers. The results so far indicate that this approach will require an infrastructure that may be costly but the benefits will outweigh this cost.

The future grid will include more renewable energy sources, price-responsive demands, and competition among suppliers. Older, less efficient, and dirtier generation units are likely to be retired. To reliably and economically meet demands for electricity in the future, sound investments in new generating capacity must be made soon. Developing more efficient ways to optimize under uncertainty and compute equilibria among competitive suppliers will enable candidate investments to be evaluated accurately.

The future grid will rely on data and communications for health monitoring and control. From the consumer to the supplier, sensors will drive economic decisions and operational control algorithms. Situational awareness will be a key component of this future grid and will enable humans to effectively deal with problems and optimize solutions. Model-less reliability assessment will exploit this direct data driven feature and provide improved diagnosis techniques. The assessment will be robust to topology changes and ensure current state measurement, which will facilitate more secure operation.

5 Conclusions

New technologies of renewables with large uncertainties, smart and controllable appliances, improved and less expensive communications create new challenges and risks for the power grid but also new opportunities. The research community should respond to develop new approaches and new paradigms to use the controllability of these resources towards a system that will improve economics, the environment and the reliability of the system. In this research project we have been developing a new approach for monitoring and controlling the plethora of small resources via a coordinated (hierarchical) optimization and control approach.

Long term planning has always been complicated by uncertainty but the levels, dimensionality, and volatility associated with uncertainties that affect generation expansion planning are increasing. In this research we are reducing the number of possible future scenario paths that must be considered by focusing on how they affect the planning decisions to be made immediately. And we are investigating how competition among suppliers combines with transmission constraints and demand response to influence their separate investment decisions.

PMUs have been acknowledged as an enabling technology for transforming real-time power system operations. Despite this potential, the truth is that their utilization in real-time operational reliability monitoring has been limited. The proposed research has the potential to provide tools for operators to address several operational reliability issues.

References

[1] Grijalva, S. *Direct Use of Planning Applications in the Real-time Environment*. IEEE Transmission and Distribution Conference and Exposition, Chicago, Illinois, April 21-24, 2008.

[2] Grijalva, S.; S. Dahman, K. Patten, and A. Visnesky. *Large-Scale Integration of Wind Generation Including Network Temporal Security Analysis*. IEEE Transactions on Energy Conversion, vol. 22, no. 1, March 2007.

[3] Hubert, T.; S. Grijalva. *Home Energy Manager: A Consumer-Oriented Interactive Tool to Optimize Energy Use*. Accepted Paper. IEEE International Conference on Consumer Electronics, Las Vegas, Nevada, January 9-12, 2011.

[4] Liang, J.; S. Grijalva, and R. Harley. *Increased Wind Revenue and System Security by Trading Wind Power in Energy and Regulation Reserve Markets*. IEEE Transactions on Sustainable Energy. (under review).

[5] Wang, Y. *Scenario reduction heuristics for a rolling stochastic programming simulation of bulk energy flows with uncertain fuel costs.* [dissertation]. Iowa State University, Ames, Iowa, 2010.

[6] Heitsch, H.; and W. Römisch. *Scenario reduction algorithms in stochastic programming. Computational Optimization and Applications*. [journal reference] vol. 24, pgs. 187-206. 2003.

[7] Feng, Yonghan; and Sarah M. Ryan. *Scenario Construction and Reduction Applied to Stochastic Power Generation Expansion Planning*. Technical report, Iowa State University, 2011.

[8] Feng, Yonghan; and Sarah M. Ryan. *Application of Scenario Reduction to LDC and Risk-based Generation Expansion Planning*. Forthcoming in Proceedings of IEEE Power Engineering Society General Meeting, San Diego, California, July 2012.

[9] Ryan, Sarah M.; A. Downward, A. Philpott, G. Zakeri. *Welfare Effects of Expansions in Equilibrium Models of an Electricity Market with Fuel Network*. IEEE Transactions on Power Systems, vol. 25, no. 3, pgs.1337-1349, 2010.

[10] Meliopoulos, A.P. Sakis; George Cokkinides, Renke Huang, and Evangelos Farantatos. *Integrated Smart Grid Hierarchical Control*. Proceedings of the 45th Annual Hawaii International Conference on System Sciences (HICSS), Maui, Hawaii, January 4-7, 2012.

[11] Meliopoulos, A.P. Sakis; George Cokkinides, Renke Huang, Evangelos Farantatos, Sungyun Choi, Yonghee Lee, and Xuebei Yu. *Smart Grid Infrastructure for Distribution Systems and Applications*. 44th Annual Hawaii International Conference on System Sciences (HICSS), Koloa, Kauai, Hawaii, January 4-7, 2011.

[12] Farantatos, Evangelos; Renke Huang, George Cokkinides, and A.P Sakis Meliopoulos. *Implementation of a 3-Phase State Estimation Tool Suitable for*

Advanced Distribution Management Systems. Power Systems Conference and Exposition (PSCE), Phoenix, Arizona, March 20-23, 2011.

[13] Meliopoulos, A.P. Sakis. *Computer Aided Instruction of Energy Source Utilization Problems*. IEEE Transactions on Education, vol. E-24, no. 3, pgs. 204-209, August 1981.

[14] Meliopoulos, A.P. Sakis; George Cokkinides, Renke Huang, Evangelos Farantatos, Sungyun Choi, Yonghee Lee, and Xuebei Yu. *Smart Grid Technologies for Autonomous Operation and Control*. IEEE Transactions on Smart Grid, vol. 2, no. 1, March 2011.

[15] St. Clair, H. P. *Practical Concepts in Capability and Performance of Transmission Lines*. IEEE Transaction Power Application Systems, Part III, vol. 72, no. 2, pgs. 1152-1157, January 1953.

[16] Gutman, Richard; P. Marchenko, and R. Dunlop. *Analytical development of loadability characteristics for ehv and uhv transmission lines.* IEEE Transaction Power Application Systems, vol. PAS-98, no. 2, pgs. 606 –617, March 1979.

[17] Gutman, Richard. *Application of line loadability concepts to operating studies*. IEEE Transaction Power Systems, vol. 3, no. 4, pgs. 1426-1433, November 1988.

[18] Millman, J.; and C. Halkias. *Electronic Devices and Circuits*, New York, New York: McGraw-Hill, 1967.

[19] Chow, J.; A. Chakrabortty, L. Vanfretti, and M. Arcak. *Estimation of radial power system transfer path dynamic parameters using synchronized phasor data*. IEEE Transaction Power Systems, vol. 23, no. 2, pgs. 564-571, May 2008.

[20] Meliopoulos, A.P. Sakis; and et al. *PMU data characterization and application to stability monitoring*, in Proceedings of Power Systems Conference and Exposition, 2006.

[21] Vu, K.; M. Begovic, D. Novosel, and M. Saha. *Use of local measurements to estimate voltage-stability margin*. IEEE Transactions on Power Systems, vol. 14, no. 3, pgs. 1029-1035, August 1999.

[22] He, T.; S. Kolluri, S. Mandal, F. Galvan, and P. Rastgoufard. *Identification of weak locations in bulk transmission systems using voltage stability margin index*. Proceedings from IEEE PES General Meeting, Denver, Colorado, 2004.