Multi-objective Wide-area Control of Renewable and Distributed Energy Resources for the Operation of Smart Grids

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1. Critical National Need

The efficient operation of many complex systems requires real-time optimization to achieve feasible and desirable behavior. In order to apply conventional optimization methodologies, models of the behavior of the system must be developed and validated. However, complex systems are usually distributed, constantly changing, and involve a high degree of uncertainty. Furthermore, the characteristic dynamics of such systems is not easily modeled with traditional mathematical constraints. The behavior of these complex systems is easily and naturally expressed with if-then rules. Hence, new optimization methodologies that operate on domains defined by dynamic rules would greatly enhance the ability to operate efficiently. It would enable complex systems to learn and adapt to changing environmental conditions in an optimal manner.

A visible and timely example is the operation of a smart power systems grid. The smart grid is a complex collection of distributed, strongly coupled, subsystems. The basic operations of those subsystems are characterized by first principles, such as Kirchkoff laws, Ohms laws and other conservation principles. However, the dynamics of these subsystems is affected substantially by operational, economic, and regulatory rules which are expressible with quantifiable if-then rules. New methodologies must be able to include both classic mathematical constraints and constraints that are expressible by rules.

The drawback to transforming rule-based constraints to standard mathematical expressions is that it requires drastic simplification, and requires domain experts to be optimization experts as well. An advantage to optimizing with rule constraints directly is that domain experts can effectively interact with the optimization technology.

Moreover, the extensive network of distributed resources is a symbolic feature of the smart grid that can only be accurately modeled with rules. Any smart grid system will be composed of heterogeneous components, such as small wind turbines, PV panels, distributed energy storage (batteries, flywheels, etc.), electric water heaters, A/C systems, PHEV charging stations and other smart loads. These components have widely different operational behaviors, and their interactions are specified by protocols of operation encoded by if-then rules. To achieve system reliability and efficiency of the smart grid, new optimization technologies must be developed.

The current technology for the power grid does not have the necessary capability to meet the requirements of a smart grid. The current approach of controlling separate optimization modules, such unit commitment, economic dispatch, and optimal power flow models, cannot incorporate the integrated nature of a distributed smart system. It assumes a centralized and hierarchical system, whereas the savings of a smart grid presumes distributed decision making and opportunistic behavior. The smart grid must be able to respond to distributed system signals and events, and mitigate the variability from renewable energy sources.

Research is needed to develop an intelligent, priority-based, multi-objective, rule-based, optimal control methodology to co-optimize the operation of renewable and distributed energy resources to operate the modern power grid reliably, efficiently, and economically. An advanced control methodology enabled by the smart grid infrastructure must be able to address the uncertainties introduced by different system operating conditions and the distributed energy resources. The technology for the smart grid must be able to integrate design decisions at a real-time operational level, with an hourly level and daily level, and include ways for humans to interact with the complicated system in an efficient manner. New technologies for a smart grid must also address the need to develop protocols and rules that can adapt to the dynamic changes in the environment.

1.1. Modeling Uncertainties

Research on developing technologies for the smart grid must have a computationally efficient way to incorporate uncertainties that arise from the high penetration of renewable generation resources and the extensive use of distributed energy resources. One of the objectives of the technology is to provide reliable power, in the face of uncertainty. Without an advanced methodology to provide corrective action, the nation faces the possibility of rolling brown-outs, and even black-outs. Thus research on rule-based optimization is necessary to develop a methodology that can deliver reliable power when facing uncertainties from the power generation using renewable energy sources, and the uncertainty of demand that will be adjusting to price and availability.

1.2. Distributed Resources Models

Responsive distributed generation, energy storage, and demand response programs can actively participate in power system operation and respond to real-time price signals, system frequency variations, system voltage changes, or other control signals. However, the extra controllability gained through distributed resources may not necessarily facilitate power grid operation, unless the operation of these distributed resources are predicable and properly coordinated. Therefore, the modeling of the distributed resources and their responses to different system operational rules is critical.

1.3. Multi-Resolution Data Models And Model Reduction

A multi-resolution data model and a methodology, which implements directed, real-time data reduction, reconstruction, and aggregation, must be developed. The smart grid new methodology must enable real-time situational awareness of the power grid throughout various levels. While addressing data at various levels of detail, the proposed technology must be computationally efficient and easy for system experts to modify and utilize.

1.4. Multi-Objective Optimal Control

The new smart grid requires an intelligent control framework to coordinate the operation of energy storage devices and smart loads to provide multiple-paid-energy services. Distributed energy storage devices and smart loads can potentially reduce energy production and enhance grid performance, reliability, and security. However, their individual sizes are small (usually less than 1MW), making them expensive and hard to control and monitor. Therefore, providing multiple services is essential to yield a satisfactory investment return, which can significantly change the course of smart grid acceptance and development. A new technology must enable benefits that the future smart grid is expected to offer. It must also be practical for implementation and balance the multiple objectives inherent in a complex system such as the smart grid.

1.5. Rule-Based Optimal Control

In a smart grid implementation, where power will flow in two directions, the hierarchy of protocols will have to be made more flexible. Generation or consumption of power may occur at multiple points in the power grid, and the operational and coordinating rules must be able to dynamically account for this in a distributed fashion. Research is required to develop protocols and operational rules that will result in an effective optimal system-wide behavior.

The control methodology must also recognize and integrate autonomous rule-based components with classical control systems to optimize system behavior in near real-time. The smart grid must be able to mitigate the intermittent generation resources using distributed energy resources (DERs). The penetration of distributed energy resources (DERs), such as rooftop-PV, small wind turbines, distributed energy storage devices, and demand response programs, are expected to increase dramatically. Advanced communication, protection, and control technology are needed to coordinate DERs to maintain system reliability and efficiently. In addition, the deployment of DERs should be well controlled so that it will make the load forecast more accurate instead of having greater variations. Traditionally, control actions are performed on a few control centers within a balancing authority (BA). It is impractical for the few control centers to control the numerous DERs and optimize their operation. Hence, it is necessary to design intelligent controllers that reside at distribution substations to optimize the operation of DERs and coordinate with each other through the transmission level control centers. Because multiple control objectives need to be implemented and a large number of different DERs need to be dispatched, rule-based intelligent control algorithms to make cost-effective decisions are desired to select different control objectives and rank different DERs by performance, economics, and availabilities for different operation cases.

In addition to generation and transmission level rules, a comprehensive power system must also recognize that operational rules must account for behavioral rules, experiential rules, government regulations, company requirements, etc. These rules are intended for the distributed components and will prescribe local operational behaviors that contribute to optimal behavior of the system. The rules will also include coordination protocols that will define how various components synchronize with one another. Not only must rules and protocols be designed, but they must be adaptive to respond to system changes.

2. Societal Challenge

More than any other system, the power system is determined by an amalgamation of rules and physical principles. Up until now, the physical principles are treated independently of the behavioral rules. These rules include contract agreements between providers, inter-regional government regulations, market protocols, and internal operational rules. There have been attempts to create optimization systems that incorporate these elements, but they have not been integrated. The current optimization systems also require enormous computation, and they are not scalable to meet the demands of a smart grid with renewable energy sources. They also cannot handle the bi-directional flow of power anticipated with the smart grid.

The current optimization approaches must make simplifying assumptions in order to be solvable in a practical amount of time. Radically new optimization models are necessary that can integrate operational rules and protocols with traditional mathematical expressions in an optimization context. Rules provide a more flexible and natural way to express realistic operational and behavioral systems, and thus reflect reality more closely. In addition, the design of the evolving power system that includes renewable energy sources and smart loads may be considering the impact of government regulations, market design or operational protocols, and new research is called upon to identify an optimal set of rules that elicit the best system performance.

The research must be able to address distributed decision-making and dynamic control of the power grid integrating renewable energy sources with smart loads to achieve a reliable and cost-effective power system. This will contribute to the national need for effective ways to incorporate heterogeneous sources of generation and provide an efficient and reliable power system, in the future.

3. How Rule-based Technologies Meet National Needs

The integration of renewable energy sources and smart loads into the current power grid is a necessity; however, effective management strategies and transmission coordination protocols for handling uncertain weather conditions and dynamically changing consumer loads are elusive. To avoid pending rolling brownouts and even blackouts, one must develop new methodologies to coordinate a complex network of decision entities that control the behavior of the system in a cost-effective and reliable manner.

Transformative research is needed to advance the reliability of America's power grid while integrating clean energy from renewable sources. It is necessary to provide a means to balance uncertain supply and demand to provide an efficient and robust system. A rule-based optimization methodology that can accommodate dynamic changes, and reduce the likelihood of brownouts, and be cost-effective will improve our quality of life and allow America to provide leadership in implementing a stable power grid with renewable energy.