Massively Distributed Computational Intelligence For A Self-organizing Power Grid

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Index Terms

Smart Grid, Computational Intelligence, Distributed Decision-making

1 Motivation & Problem Description

The North American electric power grid is the world's largest single machine ever built by man. It is spatially and temporally complex, non-convex, nonlinear and non-stationary with uncertainties at many levels. Its efficient, reliable and safe operation and control is a formidable challenge as clearly demonstrated by the 2003 Northeast American Blackout [1]. Furthermore, it is becoming increasingly apparent that challenges posed by rising global energy demand, shrinking traditional energy sources and the existential threat of global climate change cannot be satisfactorily addressed by incremental advances in fossil fuel based energy production and distribution.

Renewable energy resources offer clean alternatives to fossil fuels. They produce little or no pollution or greenhouse gases, are widely available, and will never run out. A sustainable energy policy demands a substantial increase in the use of renewable energy sources such as wind and solar farms, coupled with a massive increase in energy efficiency, supporting a transition towards a decarbonized economy.

Long distance energy transmission, distributed power generation and smart grid systems could become key elements towards fulfilling this vision. However, such a massive deployment of renewable energy sources poses new technological and organizational challenges for the existing infrastructure. The fluctuating nature of renewable energy, and the geographical restructuring of conventional power generation is rapidly making existing transmission and distribution technologies obsolete. The traditional philosophy of meeting consumer demands via centralized allocation of power would not be effective in a large-scale distributed environment due to sheer number of decision variables, and uncertainties caused due to random fluctuations in generation and load. Furthermore, such a massively interconnected system forms a complex network whose dynamics is poorly understood by currently available analytical tools. According to data from the Energy Information Administration, net generation in the US came to over 3.9 billion megawatt hours (MWh) in 2005 while retail power sales during that year were about 3.6 billion MWh, transmission losses accounting for 239 million MWh, or 6.1% of net generation; which translates to a net cost of $19.5 billion to the US economy; figures which have not improved in the recent years.

1.1 Research Objective

In the context of the above discussion, the objective of the proposed research (See Fig. 1) may be verbalized as follows:

> *Development of viable analysis and algorithmic tools to facilitate both near-term and long-term re-engineering of the power grid to allow seamless integration of both small and large generation sites possibly operating on a variety of renewable technologies, scattered over wide areas, with the ability to optimally, reliably and safely manage unavoidable fluctuations in supply and loads.*

• **Near-term Re-engineering (Static Grid Topology):** The proposed computational tools admit near-term field deployment requiring minimal cost-effective changes to the existing power infrastructure. This is a crucial point; any viable modernization must be aware of the economic implications of a large-scale re-engineering; which alone may make an otherwise sound approach impractical. The proposed research allows for near-term incremental transitions; aimed at effectively leveraging the existing capabilities in the process of transitioning towards the use of large-scale distributed computational intelligence.

Our envisioned approach for near-term rengineering uses autonomous distributed optimization of generation schedules that minimize overall generation and transmission costs and losses under stochastic fluctuations, while taking into account the realistic constraints on generation, and transmission capacities. The key control inputs in this case are the set points for nodal power injections, which are optimized to compensate the emerging continuous-time network dynamics in near-real time. Our vision delineates a novel methodology using massively distributed autonomous decision-making algorithms, that propagate local information across the network, ensuring near-global optimality of local decisions on power injections. Such situation-aware adaptive capability also lends significant operational resilience; allowing fast and effective autonomous responses to localized faults preventing large-scale failure cascades. In particular, the proposed distributed algorithms are capable of not only computing optimal power injections, but also simultaneously deriving optimal topological modifications to mitigate system-wide fault propagation.

• **Long-term Re-engineering (Dynamic Topology Reorganization):** The generality of the proposed approach allows one to go beyond the capabilities that are offered within the current infrastructure, and address anticipated control problems in future infrastructures with large-scale dynamic reorganization capabilities. In addition to optimizing nodal injections, one is then required to compute optimal structural re-organizations of the complex power network in near-real time, with the

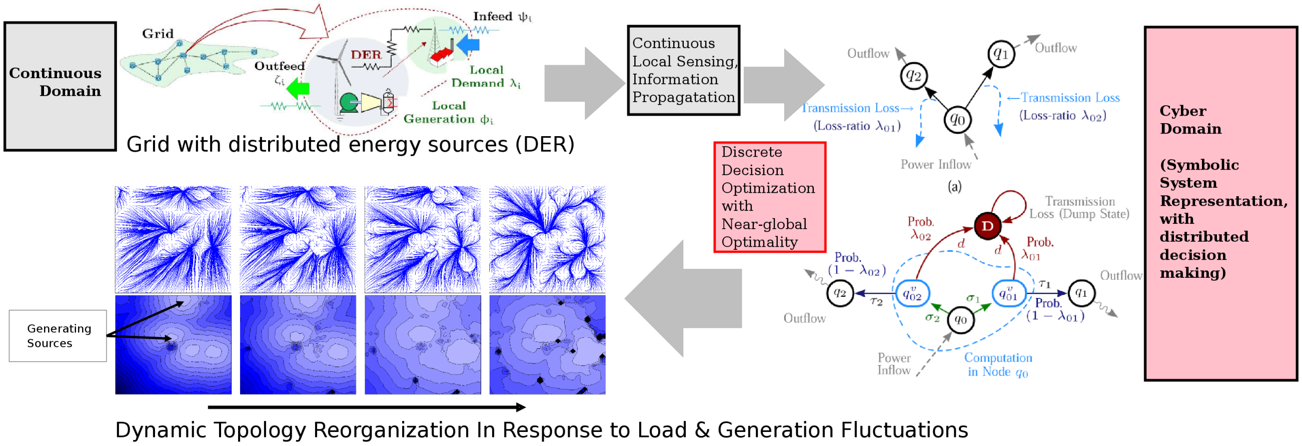

Fig. 1: Massively distributed decision-making combined with real-time continuous sensing leading to the realization of a self-organizing supersmart power grid. The porposed decision algorithms offer provable guarantees on performance, reliability and robustness.

objective of maximizing power throughput, while minimizing congestion, and failure probabilities. The proposed algorithms are capable of efficiently solving this formidable decision problem, and affect dynamic contextual topology adaptations at a massive scale in response to percolated information on demand, generation and failure dynamics; thus realizing the proverbial supersmart grid with capacity for self-healing via situation-aware self-organization.

2 Solution Philosophy & Key Innovations

Our solution philosophy is based upon the rationale that the power routing and decision-making in large grids can be modeled as a constrained optimal control problem for a Decentralized Markov Decision Process (DMDP), which can be effectively and efficiently carried out using rigorous formulations within the framework of Probabilistic Finite State Automata (PFSA). We model the network dynamics and its complex interactions within a probabilistic framework, and derive scalable solutions to the stated problems, while taking into account realistic constraints and stochastic fluctuations in generation capacities, transmission and demands. *Of particular theoretical interest is the ability of the proposed technique to provably control the upper bound on the deviation of the computed solutions from the global optimal using solely information that is either local, or that which can be queried locally.* We envision continuous local monitoring of pertinent variables to identify the relevant local parameters of the probabilistic automata modeling power flow over the complex transmission network. Nonlinear modeling of the time varying dynamics of an electric power system is extremely challenging using classical techniques, but learning paradigms such as neural networks have been successfully used to model such dynamics on-line in near-real time [1]. Our use of PFSA based problem representations, instead of standard MDP formulations, allow us to set up the ensuing large-scale decision problem as that of performance maximization of probabilistic automata, and obtain solutions using the recently reported quantitative measures of probabilistic regular languages [2; 3]. This shift of modeling paradigm is the quintessential insight that leads to unprecedented computational efficiency, achieving near-global optimality in polynomial time. The performance maximization of the probabilistic network model subsequently allows one to reduce the generation scheduling problem to a relatively simpler distributed linear program albeit with stochastic fluctuations in input parameters. *The fundamental strength of the proposed architecture is the realization of the parameter estimation, network optimization, and the generation scheduling functions as conceptually distinct distributed functional modules.* These modules are not operationally decoupled; estimated flow parameters dictate the computation of language-measure-theoretic network performance, which in turn dictates the input parameters for the generation scheduling problem, and specific schedules then affect the network flow parameters primarily due to intrinsic non-linearities in the power flow equations. However, the ability to carry out these functions in conceptually distinct modular forms is crucial for not only analyzing and provably verifying dynamic properties of robustness and stability, but also deriving theoretical guarantees on global quality of service by improving system-wide dynamic and transient performance. Key innovations are:

• **Modeling of power grid with probabilistic automata:** We propose to develop comprehensive methodologies to effectively capture the complexities of the essentially nonlinear physics of electrical power flow within the framework of probabilistic automata. In particular, the proposed effort will delineate the variables that must be monitored (locally) to extract pertinent information on power flow statistics and the relevant local transmission costs, and formulate the subsequent in-situ computational analysis required to estimate the local parameters of the PFSA model in appropriate time scales.

• **Design of perfectly decentralized decision-making techniques for power routing and dynamic grid reorganization:** PFSA based modeling allows us to model the dynamics of large scale power routing as a DMDP, and the proposed approach will effectively solve this formidable decision-optimization problem via language-measure-theoretic simultaneous performance estimation and maximization of the stated models [4; 5; 6]. *This is the central innovation of this effort; housing a fundamental breakthrough in the theory of distributed decision-making.*

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