Modeling, Analyzing and Managing Complex Future Power Delivery Systems

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I. Summary

Socio-economic forces at play are pushing for change in power systems. The objective is to maintain and improve the electricity delivery service, avoiding astronomically expensive investments in new power lines and other infrastructure, while curbing significantly green-house gas emissions and nuclear waste. The latter entails retiring coal and nuclear plants, increasing the portfolio of wind and solar generation, as well as electrifying the transportation sector - converting most cars into plug-in electric vehicles (EV). While policies sprout throughout the world to incentivize renewables and EVs, the mechanisms for scheduling power generation have largely remained unchanged in the face of these policies. In different countries they take different forms, but they all pose significant architectural barriers to meet the goals of the most ambitious among these policies. Why are these barriers maintained? Economic calculations that discount the consequences of pollution are certainly to blame, but the reason is also technical. There is a quantum leap in information assurance, data analytics and economic sophistication that power systems would have to make in order to fulfill these sustainability goals. What wide-area computational, sensing and economic architectures are going to be up to the task? The research issues in defining these architectures are as follows.

A. Distribution side

1) **Inelasticity of the demand:** Demand-side management is considered a natural evolution of the electricity market. Large segments of the research community supports dynamic pricing based on successful but limited experimentation. However, ex-ante modeling and online control of the demand are still very rudimentary and, therefore, the effect of online scheduling mechanisms at large scales is not fully understood. This is why, in the real world of the electricity market, the notion of wide-spread residential demand response, as opposed to the flexibility of large industrial operators, is considered more often a liability than a resource. While large industry is certainly an important resource to tap into, it is harder to standardize the response mechanism due to the complexity of the electricity usage and the variety of missions in large plants. In our past work [1], [5], [3], [2] we envisioned that the widespread adoption of EVs, each requiring as much energy as the rest of a typical residence combined, will be a catalyst for incorporating energy standards for flexible-demand appliances that will lead to a standardized interface and facilitate interoperability and aggregate modeling efforts. The challenge we see ahead is to be able to find a unifying and scalable aggregate description for population of heterogeneous appliances with intrinsic flexibility that is comparable to a car battery.

2) **Privacy concerns:** The implications of the possible breach of privacy associated with finely metering electricity consumption in order to decide prices, are not fully understood. Computational game theoretic analysis may reveal vulnerabilities on the consumer side that are consequences to the asymmetric collection of information regarding the consumer economic behavior. Our position is that demand flexibility should be recruited by offering discounts to attract specific forms of flexibility [4], such as deferring the charge of an EV by a certain delay, rather than offering a time-varying price for electricity, while avoiding invading the privacy of the user by analyzing the response to price in his/her consumption.

B. Generation side

1) **Poor stochastic modeling of risk in scheduling decisions:** There is a systemic bias against using opportunistically large amounts of renewable power, because of its stochastic and uncontrollable nature, notwithstanding its short-term predictability. The demand and supply models used for scheduling generation include mechanisms for forward contracts that are not sufficiently sophisticated to manage large volumes of risky generation, at least with the level of risk that exists when making scheduling decisions the day ahead on wind and solar power production. This in turn implies that the market for renewables is limited to a very modest portion of the demand that was not foreseen the day ahead, and even how to do that is not well understood. As long as we do not capitalize on information, architectural changes and proper statistical modeling to change that equation, the scheduling will continue to favor fossil fuel generation and the limited supply of available hydro power. Renewable power capacity will only add costs in terms of controlling and spilling excess power to maintain stability of the system. Research on risk-limiting dispatch [7] is an important first step in the right direction. However, the model is largely based on first-order statistics, while second-order statistics play an important role in the duration of the events that the risk-limiting dispatch approach is trying to hedge against, and we deem the analysis of this as an important direction of research, in conjunction with our load modeling efforts that quantify the temporal laxity of the aggregate controllable demand.

C. Transmission and wide area infrastructure

1) **Incomplete understanding of system risks of failure:** Part of this over-conservative approach toward compounding risk is due to limited scientific understanding of the way the grid fails. Also, any form of verification of control and protection mechanisms is based on oversimplified models for cyber-physical infrastructure. The vulnerabilities caused by the interdependency between communication network, computer systems and the grid are still poorly characterized and understood. In addition to the work that analyzed cascading failures data [15], [16] there have been efforts in applying approaches inspired by statistical physics to grasp these trends

[17], [22], [20], [19], [18], but the latter have applied too often abstractions for the escalating process that are not justifiable or reproducible based on the power flow equations. The systematic characterization of the statistics of the grid topological and electrical characteristics we is a first step in this direction [10], [11], [13], [12], [14].

2) **Aging infrastructure:** Smart Grid research initiatives helped increase the visibility of the power-system state by supporting the expansion of the grid sensory system, particularly with the addition of synchrophasors and Smart Meters. While there is arguably a lot to be done yet in improving wide-area situational awareness, these research advances have had moderate to no impact on the the way the grid manages demand and supply of electricity as well as the mechanisms used to control its assets and their benefits are yet to be fully understood. Furthermore, incentives to install solar panels in households and business have placed significant strain on a portion of the grid that has very little instrumentation, namely the distribution grid. The controllability of the solar panel inverters remains untapped. What are the most compelling analytics and can they be relied upon to strategically learn and act with small margins of error? What are the most effective forms of control? Can computation of such control actions be pushed towards the edge of the grid, relying on advances in decentralized learning algorithms [8], [9]?

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