Position Statement

Hierarchical Control of Large Population of Heterogeneous Dynamic Smart Grid Assets

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Renewable energy resources, electric vehicles, smart appliances, distributed storage, and distributed generations are expected to play a key part in the future sustainable energy systems. High penetration of these assets will introduce large uncertainties and dynamics to the grid, creating significant challenges to its efficient and reliable operation. To address this challenge, merely relying on the economic incentives to reduce or shift energy use on large time scales is not enough; advanced control technologies coupled with market mechanisms that can achieve fast and reliable response is of crucial importance to meet the challenging balancing need of the future grid.

Hierarchical Control Framework: Most existing approaches in the smart grid literature builds, either explicitly or implicitly, on certain hierarchical decision making structure. A coordination strategy typically involves two decision layers: coordination layer and device layer. The coordinator determines a coordination control signal based on some aggregate information of all the devices and some desired global objective. On the device layer, each physical device typically has decoupled dynamics and responds to the coordination signal according to a predefined rule (possibly device-dependent). The resulting hierarchically controlled system can represent many basic control/decision problems in smart grid. For example, the system can represent a demand response program in a residential neighborhood, where the coordinator represents a Load Service Entity or a Curtailment Service Provider, and the devices represent the participating loads, such as HVACs (Heating, Ventilation, and Air conditioning) or PEVs (Plug-in Electric Vehicles). The coordination signal can simply be a price signal or a direct load control signal, while each participating load can respond to the coordination signal differently depending on its dynamic state such as temperature or remaining time to deadline. Similarly, the hierarchical control framework can be used to study building power management, data center power control, PEVs charging coordination, active power control for DERs, to name a few. A generic problem across all these application scenarios involves the design of individual device response rules as well as the coordination signal based on some aggregate information about the population.

Fundamental Challenges: Although many existing works in smart grid resemble the above hierarchical structure, there is yet no theoretical framework to enable systematic analysis and design of this kind of hierarchical control systems. The main challenges are three-fold.

(i) *Heterogeneous Device Dynamics:* Controllable devices have internal dynamics, such as temperature dynamics of HVACs, timing dynamics of deferrable loads, SOC dynamics of storage devices, among others. In addition, the devices also need to dynamically respond to external coordination signals (such as price, direct load control signal, or power system frequency), which often creates abrupt structural changes on the internal dynamics (mode switching), thus dramatically complicating the overall device dynamics. A general modeling framework that captures all these aspects of heterogeneous responsive devices do not exist in the current literature.

(ii) *Complicated Aggregated Dynamics:* A systematic design of the coordination control requires a deep understanding of the aggregated dynamics of the device population. Such aggregated dynamics can be rather complicated due to the nonlinear individual device dynamics, user influence on the device operation (such as changing temperature setpoint, plugging in a PEV, temporarily opting-out from the program, etc), and logic-based response rules. Existing aggregated load modeling methods are mostly for homogeneous first-order TCLs (Thermostatically Controlled Loads); a general aggregated modeling framework needs to be developed.

(iii) *Lack of General Hierarchical Control Theory:* Existing theoretical tools in distributed control, decentralized control, and hierarchical systems, are not directly applicable to solve the aforementioned hierarchical control problem in the context of smart grid applications. This is partly due to the highly nonlinear device dynamics mentioned above, and due to the particular emphasis on the performance of the whole system instead of stability-related issues. It is also worth mentioning that most existing market-based coordination strategies assume static decision makers, while the nontrivial device dynamics are a key element in our framework that cannot be ignored.

Our group at OSU is currently working on developing new hierarchical control theory for various smart grid applications, especially for demand response modeling, analysis and control. Our research cross-cut all the aforementioned fundamental challenges. In particular, we have developed a unified hybrid system framework to model responsive loads under a variety of demand-response programs. Based on the hybrid system load model, we have also developed a general aggregated modeling framework that can accurately capture the aggregated heterogeneous load dynamics. These unified models enable us to systematically study the proposed general hierarchical control problem. We believe this research direction will significantly advance our understanding in hybrid systems and hierarchical control systems, and enable systematic design of various smart grid control strategies with guaranteed performance and reliability.