Architecting an Internetwork of Autonomous Microgrids: From the Internet Architecture to a Clean-Slate Power Network Architecture

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Both communication and power networks are massive nonlinear feedback control systems. Both started around the beginning of last century to provide a single commodity (telephone service and electricity), with similar engineering, economic, and regulatory structure. A hundred years in, the Internet has revolutionized communication industry, completely replacing original circuit switching architecture of telephony, restructuring landscape of the industry, and unleashing a wave of innovations with impacts far beyond communications. The evolution of electricity industry has been less explosive in comparison. However, power network will undergo in next few decades similar architectural transformation that telephone network has gone through in last two, and this transformation is expected to create an Internet equivalent of power network, with equally far-reaching impacts. Foundational theories and new architecture are needed to help guide this transformation. We believe that incremental enhancements to current power network architecture are inadequate to meet future needs, while risking making the system much more complex and difficult to manage. Instead, a redesign of power network architecture from scratch, which offers improved abstractions, performance, and functionality based on new design principles, is required.

In particular, future power grid will consist of hundreds of millions of distributed energy resources (DERs) such as photovoltaics, wind turbines, electric vehicles, smart batteries, inverters, and smart appliances. These hundreds of millions of end points are not merely passive loads as are most endpoints today, but active endpoints that may generate, sense, compute, communicate, and control. Given such a system and suppose that we redesign power network from scratch, how should we interconnect, control, and manage these DERs and optimize their operation? Motivated by the Internet architecture and driven by the scalability requirement, we propose to architect power grid as an internetwork of microgrids. Each microgrid is made autonomous through local sensing, computation, communication, and control, in such a way to make the microgrid self-sufficient and behave as a single dispatchable entity as much as possible. At larger scopes, these microgrids coordinate and cooperate to balance supply and demand, support voltage, and regulate frequency for each other to achieve systemwide efficiency, reliability, and robustness. The system we envision is more than just a two-level hierarchy of single microgrid - internetwork; a microgrid may itself be an internetwork of smaller microgrids. This recursive internetwork architecture captures distributed structure of future smart grid, and more importantly, greatly reduces management and control complexity, which can effectively address critical challenges imposed by nondispatchable renewable generation and the sheer scale of future system. We need to delineate and develop an overarching framework to reason about architectural questions such as the design goals (e.g., to allow distributed management, to support different types of energy services, to allow plug-n-play of renewables, to support plug-n-play microgrids) underlying the internetwork of microgrids and the design principles (e.g., layering, division/placement of functionality between the network and the endpoints) that can enable power network to fulfill the design goals. At the core is the development of a layered control architecture that centers on the concept of "control as a service": the network should provide a set of common control services such as voltage support to various applications such as EV charging, and an application will call and synthesize these control services on the fly to meet performance specifications. We propose to develop foundational theories and design specific enabling mechanisms and algorithms for the layered control architecture for the internetwork of microgrids, as well as jointly design the required information and communication platform.

Architecture determines how the various control mechanisms should be organized and what information should be communicated among them. A good architecture ensures efficiency and robustness and enables innovations; a bad one freezes them out. Despite its importance, there is unfortunately not enough research on power network architecture, nor is there any serious investigation of learning from other existing and successful network architectures such as the Internet architecture. We should undertake the important question of power network architecture design, at this critical time when power network is undergoing a fundamental transformation and many premises and conditions that led to the current architecture have changed and will not exist any more.