Embedding and Extracting Ubiquitous Flexibility in Microgrids from Distributed Cyber-Physical Resources

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Author: Le Xie, Department of Electrical and Computer Engineering
Texas A&M University, USA. Email: Lxie@ece.tamu.edu. Phone: +1)979-845-7563

Federal and state governments have invested billions of dollars deploying millions of smart meters and distributed energy resources (e.g. photovoltaic generators) as a major part of the smart grid initiative. The anticipated payback from the new investment in electric distribution grid is primarily (a) closer-to-real-time monitoring of meter-level power consumption; (b) improved flexibility from well incentivized consumers; and (c) higher penetration of distributed sustainable energy resources [1]. As the hardware deployment gets close to completion in many regions, a fundamental question arises: *what is the value proposition for such an improved infrastructure, and what is the "killer app" for hundreds of millions of consumers in a smarter distribution grid?*

A key to answering this question is that individual resources' benefits must be well aligned with system-level objectives at value. In future grid operation where much higher uncertainties arise due to the presence of variable energy resources, ubiquitous flexibility embedded in distributed resources in response to sharper near real-time knowledge will be increasingly valuable [2].

As shown in Figure 1, We envision a future distribution grid composed of many interconnected microgrids with pervasive intelligent agents (generators and consumers with smart computing/communication/control capabilities). Their capability and willingness to participate in provision of multi-time-scale flexibility will enable smart microgrid operators to provide much cleaner and more affordable electricity services at higher reliability. At the core of this vision lies the scientific challenge of incentivizing, modeling, and controlling the flexibility extracted from hundreds of millions of microgrid-level resources.

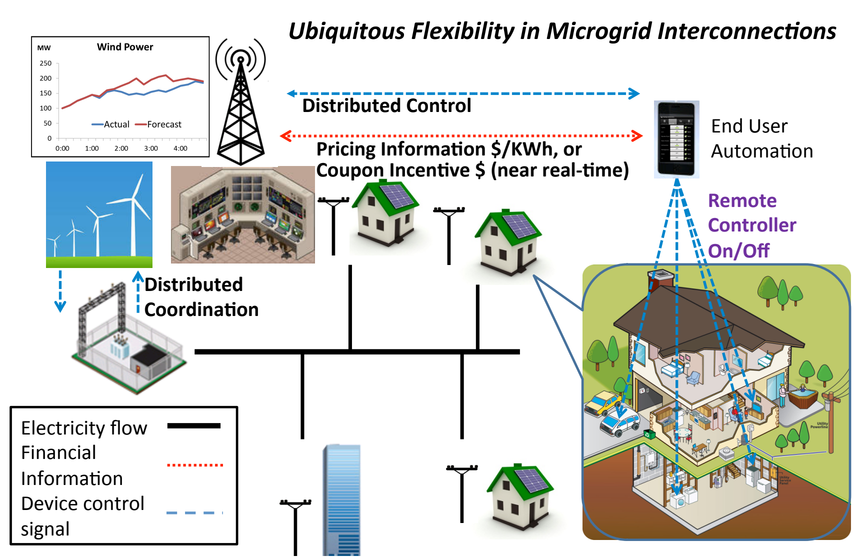

Figure 1: Vision: Embedding and Extracting Ubiquitous Flexibility in Microgrid Interconnections

In the past few years, the author and the collaborators have focused their work on **(i)** enabling flexibilities at many individual component level, such as coupon-incentive based demand response [3] and coordination of energy storage with wind [4, 5]; and **(ii)** extracting flexibilities through coordinated control of aggregated resources at different time-scales [6]. Starting from the preliminary success at resources' level, this position paper proposes a systematic framework that integrates *physics-based* and *data-driven* models of distributed cyber-physical energy resources to enable ubiquitous provision of multi-time-scale flexibility at value in future distribution grids. Today's modeling of electric energy systems is either purely based on first principles which suffers significantly from the ever-increasing complexity of non-uniform devices, or is purely based on computer science data-driven approaches which lose the fundamental physical insights of electric power networks. In sharp contrast, the proposed holistic modeling approach will combine *for the first time* advances from (1) physics-based modeling and control of new energy storage resources; and (2) data-driven modeling of heterogenous load resources. Such a cyber-physical model and control framework provides the intellectual basis for many system-theoretical breakthroughs to be translated in improved operation of microgrid interconnections. Sufficient flexibilities provided from such microgrid interconnections can then be used to reduce the burden and stress at transmission-level operations, and result in overall more efficient and reliable electricity services in the future.

Once successful, this framework will result in *hundreds of millions of dollars cost savings annually* and much higher penetration of *clean sustainable energy resources* at distribution grid level. Based on this bottom-up approach, the proposed efforts could also lead to commercialization of many flexibility technologies to penetrate into the legacy power infrastructure.

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