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Smart Grid: Overview, Issues and Opportunities. Advances and Challenges in Sensing, Modeling, Simulation, Optimization and Control

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The genesis of early power systems and electric power grids during the past 130 years was enabled by automation and control of electromechanical machinery and power delivery networks. Today's end-to-end power and energy systems (from fuel source to end use) fundamentally depend on embedded and often an overlaid systems of sensors, computation, communication, control and optimization. There are even more opportunities and challenges in today's devices and systems, as well as in the emerging modern power systems – ranging from dollars, watts, emissions, standards, and more – at nearly every scale of sensing and control. Recent policies combined with potential for technological innovations and business opportunities, have attracted a high level of interest in smart grids. The potential for a highly distributed system with a high penetration of intermittent sources poses opportunities and challenges. Any complex dynamic infrastructure network typically has many layers, decision-making units and is vulnerable to various types of disturbances. Effective, intelligent, distributed control is required that would enable parts of the networks to remain operational and even automatically reconfigure in the event of local failures or threats of failure.

This presentation provides an overview of smart grids and recent advances in distributed sensing, modeling, and control, particularly at both the high-voltage power grid and at consumer level. Such advances may contribute toward the development of an effective, intelligent, distributed control of power system networks with a focus on addressing distributed sensing, computation, estimation, controls and dynamical systems challenges and opportunities ahead.

Keywords: Smart grids, self-healing energy infrastructures, uncertain dynamical systems.

1. Focus

Electric power systems constitute the fundamental infrastructure of modern society. Often continental in scale, electric power grids and distribution networks reach virtually every home, office, factory, and institution in developed countries and have made remarkable, albeit remarkably insufficient, penetration in developing countries such as China and India.

Once "loosely" interconnected networks of largely local systems, electric power grids increasingly host large-scale, long-distance wheeling of power (the movement of wholesale power from one company to another, sometimes over the transmission lines of a third party company) from one region to another [1–7, 17, 34]. Likewise, the connection of distributed resources, primarily small generators at the moment, is growing rapidly. The extent of interconnectedness, like the number of sources, controls, and loads, has grown with time. In terms of the sheer number of nodes, as well as the variety of sources, controls, and loads, electric

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power grids are among the most complex networks ever made.

The term "smart grid" refers to the use of computer, communication, sensing, and control technology which operates in parallel with an electric power grid for the purpose of enhancing the reliability of electric power delivery, minimizing the cost of electric energy to consumers, and facilitating the interconnection of new generating sources to the grid [4–7].

Control systems are needed across broad temporal, geographical, and industry scales—from devices to power-system-wide, from fuel sources to consumers, from utility pricing to demand response, and so on. With increased deployment of feedback and communication, opportunities arise for reducing consumption, for better exploiting renewable sources, and for increasing the reliability and performance of the transmission and distribution networks. At the same time, however, closing loops where they have never been closed before, across multiple temporal and spatial scales, create control challenges as well. The control systems community has a very rich history of making pioneering contributions both the to theory as well as developing important applications in this area, they range from sensing to computation and visualization, estimation, optimization and controls – from devices and machinery to high-voltage grids to local distribution systems [2–33, 40–50].

How to manage or control a heterogeneous, widely dispersed, yet globally interconnected system is a serious technological problem in any case. It is even more complex and difficult to control it for optimal efficiency and maximum benefit to the ultimate consumers while still allowing all its business components to compete fairly and freely. This paper provides an overview of smart grids and the pivotal role that the control systems community can play with the goal of increased agility, security and resilience for smart grids and large-scale layered systems.

Societal and governmental visions for the smart grid will require the engagement of the controls community for their realization. Feedback, optimization, estimation, dynamics, stability... these and other control system concepts are core to smart grid technology. In many ways, the smart grid <u>is</u> a control problem!

2. Synopsis

Recent policies in the U.S., China, India, EU, UK and other nations throughout the World, combined with potential for technological innovations and business opportunities, have attracted a high level of interest in smart grids. Nations, regions and cities that best implement new strategies and infrastructure may reshuffle the world pecking order. Emerging markets could leapfrog other nations:

- **U.S.** investment is at about $7 billion in smart grid technologies
- **China** invested $7.3 billion; will spend $96 billion in smart grid technology by 2020
  - China's energy needs to double by 2020
  - Many changes will happen in the homes themselves
  - China will account for 18.2% of global smart grid appliance spending by 2015.
- **South Korea** at nearly $1 billion:
  - A $65 million pilot program on Jeju Island is implementing a fully integrated grid for 6,000 homes, a series of wind farms and four distribution lines. Its leaders plan to implement smart grids nationwide by 2030.
- **Brazil**: 60% growth in electricity consumption between 2007 and 2017 with 16-34% increase in renewables from hydro, biomass and wind. But they have an aging grid that is currently a one-way power flow that needs to move in two directions.

In 2007, the United States Congress passed the Energy Independence and Security Act outlining specific goals for the development of the nation's smart grid. Section 1301 states that, "It is the policy of the United States to support the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a smart grid:

1. Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
2. Dynamic optimization of grid operations and resources, with full cyber-security…".

Smart Grid is a concept and a range of functionalities: It is designed to be inherently flexible, accommodating a variety of energy production sources and adapting to and incorporating new technologies as they are developed. It allows for charging variable rates for energy, based upon supply and demand at the time. In theory, this will incentivize consumers to shift their heavy uses of electricity (such as for heavy-duty appliances or processes that are less time sensitive) to times of the day when demand is low. As an example of these range of functionalities, in 2008, U.S. Department of Energy (DOE) defined functions of a smart grid as:

- "Self-healing" from power disturbance events
- Enabling active participation by consumers in de response
- Operating resiliently against physical and cyber attacks
- Providing power quality for 21st century needs