# Control Challenges in Microgrids and the Role of Energy-Efficient Buildings

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## I. INTRODUCTION

It now seems inevitable that power grids of the future will be massive stochastic networks whose nodes are themselves microgrids comprising generation and storage units, inverters and power conditioning elements, together with controllable aggregations of appliances and other load classes. There will be significant amounts of power coming from wind, solar, and cogeneration enabled by combined heat and power plants (CHPs), and there will be new opportunities for demand response (DR) and ancillary services coming from grid-specific communication technologies that will coordinate energy storage, distributed energy resources (DERs), and flexible schedulable loads connected within low-voltage distribution networks. As power grids move away from centralized generation sources toward a system with large numbers of small and distributed production units, novel information and communication concepts will be needed to ensure secure and reliable power delivery to consumers whose requirements are themselves increasingly varied, although also often flexible.

**This special issue brings together recent research on the efficient use of energy in commercial, residential, and other types of buildings and facilities.**

The combination of residential and commercial buildings accounts for approximately 40% of the annual energy consumption in the United States [4], and similar statistics apply worldwide [5]. Commercial buildings represent 45% of that figure. Any opportunity to improve efficiency in buildings will open the door for significant energy savings throughout the world. Such opportunities exist: research has shown that up to 40% of the energy used by HVAC systems in commercial buildings is wasted due to faulty operation [2]. There are many other opportunities for improved efficiencies, including increased utilization of nearby DERs such as wind and photovoltaics, thereby reducing the fraction of generated energy that is dissipated in line losses associated with long-distance transmission lines.

By appropriately implementing a smart building operator (SBO) within a building automation system (BAS), recent research has shown that energy distribution through facility microgrids can be simultaneously optimized for efficiency, occupant comfort, and the building's ability to participate in DR power markets. (See, for example, [6]–[8].) This work makes certain assumptions about the homogeneity of appliances that comprise the load networks within the facility microgrid. While such assumptions may be valid in some new construction and certain other ideal cases, the built environment is largely heterogeneous, and variations

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across buildings make it difficult to offer universally applicable algorithmic solutions to energy management. To address this challenge, a good deal of current research is aimed at designing data structures that will facilitate the collection and interpretation of real-time data from sensor streams so as to enable new approaches to building automation. Self-describing sensors [9], [10] and grid-friendly appliances [11] will become integral parts of the *Internet of Things*, making it possible to make both future and legacy buildings efficient users of electric energy.

In order for advanced facility microgrids to achieve their full potential, they must be designed within the large contextual framework of existing power grid energy management systems (EMSs). Going forward, research is needed to ensure that future EMS architectures will be capable of accommodating interactive information exchange between different layers of energy grids across all scales of aggregation. EMSs must increasingly satisfy the needs of electricity users while at the same time supporting the penetration of new energy technologies such as wind and PV. Increased integration of distributed generation will be supported by new grid-focused IT systems that feature distributed decision making and greatly enhanced real-time communication between load networks of appliance pools, SBOs, and the various independent system operators (ISOs) at both the transmission and distribution levels. Coordinating among high-voltage transmission systems (HVTSs) and low-voltage distribution systems (LVDSs) will be needed to manage T&D network congestion so as to ensure secure and stable grid operation [14] and [15].

The purpose of this special issue of the PROCEEDINGS OF THE IEEE is to assemble and publish recent research on the efficient use of energy in commercial, residential, and other types of buildings and facilities. The papers cover a range of topics including a comparative evaluation of opportunities for improved efficiency among electric load classes in buildings, the role of smart microgrids for enabling demand-side response, utility-side-of-the-meter electricity markets, customer-side-of-the-meter electricity markets, the role of alternative energy sources, and power grid informatics. Optimized design of building networks is discussed as well. Taken together, the papers that follow provide a snapshot assessment of the current state of research on emerging opportunities associated with increasingly networked control of HVAC systems, variable-speed fans, plug-in electric vehicles (PEVs), distributed energy storage and generation, CHP microgenerators, computing, volt/var control devices, grid-friendly appliances, and smart transformers. Some of the papers deal with new approaches to improving efficiency with installed systems in existing building stocks and within the existing transmission and distribution framework of the power grid. In other cases, our authors have discussed concepts and technologies that are still on the drawing board, such as the Internet of Things, grid-friendly appliances, packetized energy delivery, direct load control (DLC), and finally power market extensions that enable real power, reactive power, and reserve transactions involving distribution network connected participants. New approaches to decentralized energy management are explored alongside potentially revolutionary new technologies such as low-voltage direct current microgrids. The past few years have seen an explosive growth of interest in new opportunities for improved operation of electric power grids, and because a great deal of research has achieved an appropriate level of maturity, this special issue is timely.

## II. OVERVIEW OF THE SPECIAL ISSUE

While the special issue touches on many themes that are universal in emerging electric power grid technologies, the main focus is on buildings—their design and efficient operation, how they can contribute to DR, and the many dimensions of the ancillary services they are capable of providing. Because of this focus, buildings and their role in microgrid operation are central in the first five papers. These articles treat both smart microgrids and energy-efficient buildings, with the main emphasis on the interplay between them. The sixth and seventh papers discuss new approaches to simulation and monitoring that have been developed to address many of the fundamentally new dynamic aspects of microgrid operation. They are followed by treatments of grid-focused real-time communication and the role of price signals in scheduling of generation resources and coordination of DR. A final paper is concerned with consumer decision dynamics and how smart microgrids must account for the ever-present uncertainties of time-varying human preferences.

The special issue begins with Mills' treatment of building benchmarking [17]. The paper describes techniques for discovering opportunities for enhancing energy efficiency in existing building stocks. Traditional benchmarking typically addresses the status of a building and how it compares to a known baseline—e.g., by comparing the building to its peers at one point in time or longitudinally. Action-oriented benchmarking extends this process by also inferring opportunities through advanced data analytics and simulation techniques. The theme of optimal operation of existing building stocks is continued in [18], where Schlueter *et al.* discuss data-driven clustering for optimally efficient creation of thermal microgrids using existing building stocks.

Emerging smart grid technologies will allow increased levels of efficiency in both commercial and residential buildings while at the same time enabling buildings to become major players in providing DR to ensure the security and efficiency of the grid. A number of the papers in the special issue show how increasingly available power electronics and schedulable loads can provide DR services to the grid—including operating reserves, frequency control, voltage support, and reactive power regulation [21]. State-of-the-art transitive DR systems are surveyed and evaluated in both [19] and [21]. The former of these also describes the recent OpenADR standard which is being adopted globally to facilitate DR implementations. DR assets in buildings include thermal energy storage capabilities of HVAC systems, parked plug-in electric vehicles (PEVs), other rechargeable batteries, and a variety of schedulable loads such as water heaters and refrigeration equipment. Kim *et al.* [21] convincingly make the case that these have a surprisingly high potential for providing DR. A route to achieving this potential is detailed in [24], where market signals in the form of locational marginal prices (LMPs) are shown to be effective in shifting the operation of certain heating assets to periods during which LMPs are low. Simulation studies have shown that thermal energy storage assets in commercial building can provide ancillary services that will reduce LMPs and operating costs.

Research on real-time analytics, grid-focused communication protocols, and aggregation strategies for network delivery of services is described in [19] and [20]. New forms of price signaling in real-time energy markets are treated in [24], and together with [25], this presents new results on distributed constrained optimization that can play a role in enabling the smart grid to achieve its full potential. Although energy markets and price signaling were studied in the 1970s and 1980s [16], extensive changes in government regulations of utilities together with remarkable technological advances over the past four decades make research on energy markets and market-based signaling more important than ever. Most important is the extension of wholesale power markets introduced in the United States in 1997 to include distributed retail participants. The associated distribution network-specific costs, congestion and reactive power compensation, together with the much higher complexity in distributed participant preferences and capabilities require breakthroughs in the science and engineering of cyber–physical systems.

Volatile power sources like wind and solar certainly present challenges to stable grid operation, but the work that is reported in the papers that follow indicates that the use of grid-aware control can increase the value of these resources. Some idea of the magnitude of variability that can be expected as renewable energy assumes that a larger share of generation capacity may be found in [22]. This paper describes two studies in which a portfolio of 54 inhabited residences were remotely monitored and controlled so that the aggregate power consumption followed a reference signal. The residences were very diverse, and HVAC was provided by heat pumps of 50 different makes and models. Because the operation of the heat pumps was controlled by a smart microgrid operator, it was possible to have aggregate power consumption of the residential network follow a reference trajectory while ensuring the comfort of individual households. Other work being reported showed that the fluctuating production of wind turbines could be regulated to provide reserve power to the microgrid.

As real-time communication becomes increasingly important among nodes occupying different hierarchical positions within the grid, there is an inevitable tendency to look for operating protocols that have characteristics in common with Internet-based communication. To facilitate network operations that provide fairness to all nodes while respecting privacy and guaranteeing security, notions of quantization that are inspired by packet-switched communication are discussed in [24] and [25]. The concept of *packetized energy* envisions temporal quantization into fixed-length intervals of energy utilization by a pool of appliances with common power ratings—especially thermostatic loads. Packetized energy is especially attractive for implementing high-bandwidth DLC protocols through which SBOs directly control load networks of smart appliances. Quantization is also a central theme in Chatzivasileiadis *et al.*'s discussion of a novel Virtual Grid Integration Laboratory (VirGIL) software platform for integrating simulation modules of various component subsystems of distribution networks [23]. Because the platform works with a variety of commercial power system software packages that are familiar to power system operators, it can be easily integrated with existing operational workflows of utilities and ISOs.

Finally, Saad *et al.* [27] discuss ideas from behavioral economics and prospect theory to argue that the dynamics of human decision making in the face of uncertainty and consumers' inability to clearly define their own preferences will be keys to understanding the complexities associated with increased consumer participation in grid operations. Before there is the widespread adoption of consumer-centric grid features such as demand-side management programs, consumer-owned energy storage and renewable energy units, and active energy trading, a better understanding of how consumers will use such features is needed.

## III. MICROGRIDS, ENERGY-EFFICIENT BUILDINGS, AND THE EVER-GROWING IMPORTANCE OF NETWORKED REAL-TIME SYSTEMS

In 2007, the Proceedings of the IEEE published a special issue with the title "The Technology of Networked Control Systems." From the vantage point of 2016, it seems naive to think that a single issue could adequately cover more than a tiny fraction of such a vast area, but the scope of new developments that have occurred and the research that has been published in the decade since the issue came out is testimony to the importance of the topic. The current special issue is in a way more narrowly focused, but at the same time it includes work on topics like distributed optimization of network performance, functional mock-up simulations of complex networks of physical devices, packetized energy, and novel communication protocols—any of which could prove to be focus topics of special issues in the decades ahead. We refer the reader to [1], and hope that this special issue will encourage further research on broader classes of device networks, theories of communication through price signaling, and hybrid networks of machines and human agents. ■

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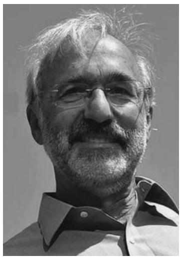

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