Research Directions for Smart Distribution Systems

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Abstract—**With increasing penetration of communication and control technologies that enable "smart grid" functionalities, an infrastructure is rapidly evolving that will support the formation of networks of sources and loads that are amorphous and dynamic, completely unlike any power system network that is extant today. Researchers are already conceiving microgrids and nanogrids that are completely autonomous, and can morph between grid-connected and islanded modes based on expediency and intrinsic objectives. This paper examines some of these architectures and discusses research needs that will drive the evolution of these "smart distribution systems".**

Index Terms—**active distribution system, island, grid, microgrid, nanogrid, smart distribution system, smart grid.**

I. INTRODUCTION

"Smart grid" is a popular moniker for what is essentially a cyber-physical energy system. The system basically comprises the traditional grid (the term "legacy system" is becoming increasingly fashionable) and unconventional (including renewable) generation and storage, augmented by enhanced instrumentation, communication, computing and data processing capability. As the "cyber layer" and its interaction with the "physical layer[1]" continue to grow, traditional methods of distribution system analysis, design, control and protection will evolve significantly to incorporate the complexities of the total system. This forthcoming evolution is staggering in its scope; we will not attempt to address it here. Reference [] provides an excellent overview of concepts and components of smart distribution systems. This paper will focus on those developments that apply to the "physical layer", namely, smart, active distribution systems or microgrids.

A microgrid is a compact, localized energy network. In general, it is a system containing distributed (located at or near load centers) generation and storage resources that can operate in islanded or grid-connected mode. Very often, it is part of the distribution system and is alternatively known as an active distribution system. The term "nanogrid", as used in the realm of energy systems, is relatively new, and is yet to acquire a universal connotation. In this paper, the term will be used to denote a microgrid that is small in extent and capacity, such as one at a building level. For instance, if one were to conceive a home with several connected storage devices such as uninterruptible power supplies and solar storage backpacks, that would constitute an example of a nanogrid. However, for all intents and purposes, nanogrids form a subset of microgrids. A "smart microgrid" is defined here as a microgrid that is equipped with some amount of intelligence and communication resources to constitute a cyber-physical system. A conceptual framework of such a system has been described in [2].

The role of smart microgrids within the vision of smart grids is to enable widespread inclusion of renewable resources, distributed storage, and demand response programs in distribution systems. At the present time, many parts of the world are experiencing widespread deployment of advanced metering infrastructures (AMI), which is considered by its proponents to be the key component of smart distribution systems and microgrids.

In the following sections we discuss some research directions that apply to smart microgrids. Some of the specific approaches described here will refer to, and depend on, existing infrastructures such as the AMI and to developing infrastructures such as home area networks (HAN). It is pertinent to mention here that methods for smart microgrids comprise an emerging field and hence the discussion here will be representative rather than comprehensive.

II. MICROGRID CHARACTERISTICS AND RESULTING CHALLENGES

With some exceptions, microgrids are characterized by dynamically changing configurations and operating modes. The distribution system may be reconfigured on the fly; units may exhaust their fuel and disconnect; storage units may switch from discharging to charging mode and vice versa; variable resources may cut in or out with changing wind or solar availability; the possibilities are numerous. "Zero energy buildings" may transition between grid-connected and off-grid modes. With the anticipated penetration of plug-in hybrid/electric vehicles, the level of chaos in the system will increase significantly. While this dynamic feature enhances the operating flexibility, it does pose challenges in terms of operations and energy management. Consequently, the associated controls can be quite complex.

If the management systems are decentralized, then considerable amounts of system information that are taken for granted in traditional approaches in centralized systems become quite challenging to obtain. Analysis and control of decentralized systems is often more challenging than that of centralized systems, because there is no central entity with system-wide information to "see" a global optimum or to resolve conflicts. In the next section, some of the approaches used to deal with these challenges will be discussed briefly; detailed descriptions are beyond the scope of this paper, but can be accessed through the cited literature.

III. RESEARCH DIRECTIONS FOR SMART MICROGRIDS

The needs and directions discussed in this paper are classified by application.

Much of the research that will enable smart microgrids are

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[1] The term "physical layer" is used here to denote the energy delivery system, comprising the generation, transmission and distribution systems, and is distinct from its use in communication and computer networking literature.

concerned with operational decision-making. Considerations in architecture of microgrids related to applications, ownership, benefits, operating modes, etc. may be incorporated in decision-making analysis. Decisions related to the type and location of the microsource (generation within the microgrid), the network configuration best suited to address specific needs, and optimum location of distribution assets such as cables, capacitor banks and energy storage elements may define the designs of microgrids. Decision-making also plays an integral role in reequipping substations in light of the proliferation of microgrids – in essence, defining the location of intelligent controls in the microgrid. Yet another aspect of microgrids that require decision-making is the economic benefits to the owners and users of the microgrids. The research needs discussed here will therefore very often involve decision-making.

A. Normal Operation

In this section we discuss analytics that apply when there is no fault *within* the microgrid. It therefore includes both grid-connected operation as well as islanded operation; as long as the microgrid itself is healthy, its operation will be considered normal.

1) Power Balance and Basic Operating Conditions

At the very least, the operation of a microgrid should satisfy (a) Kirchoff's laws, i.e., power flow conditions, and (b) operating rules, such as how to deal with situations where the capacity drops below the demand. There rules should include "community rules" that may be applicable, such as agreements between neighbors some of whom own generation while others do not. In some instances, load prioritization may involve decision-making; an example of analytics for accomplishing this is discussed below. In some instances, simple markets may exist within the community; such situations are also discussed below.

In any case, resolution of power flow and resource utilization involve the use of decision analytics. These decisions differ significantly from methods of dispatching conventional generation. Many researchers have proposed that operation of smart microgrids should be autonomous, i.e., independent of utility. Several of these [3]–[6] propose the use of multi-agent systems (MAS). The literature on MAS-control of microgrids is quite extensive, and includes centralized, decentralized and hybrid schemes.

A MAS-controlled microgrid the operating processes would consist of (a) capacity discovery within the system (island in case of disconnection from the grid) and (b) communicating appropriate control signals to the generators and loads. Ref. [6] describes a method of controlling the generators and loads to achieve power balance; [7] describes a method of capacity discovery and subsequent power flow solution in a decentralized control system. Normally this quite straightforward in a centralized system, but with agents possessing limited knowledge of system configuration and capacity this can be challenging. The method assumes neighbor-to-neighbor communications between agents and formulates the problem as a linear, discrete-time dynamic system.

2) Inclusion of Markets

Having established basic operating conditions, analytics have been used to determine more sophisticated operating strategies such as those that would maximize profits in energy and ancillary service markets [8], [9]. Ref. [10] describes an approach to utilize locational marginal price (LMP) signals to control flows and manage congestion in a microgrid equipped with flow control devices such as D-FACTS.

3) Combined Heat and Power (CHP)

Several microsources, such as microturbines and fuel cells operate at very high efficiencies when used as CHP resources. In fact, much of the early research on microgrids was motivated by taking advantage of these efficiency benefits. Some approaches for dispatching CHP units to match heat and power loads are described in [11], [12].

4) Forecasting and Load Management

Since much of the renewable sources installed in microgrids are variable in nature, forecasting of the natural elements (such as wind speed and solar radiation) underlying these sources is another very important area of research. Methods reported include time series analysis [13] and computational intelligence-based methods such as genetic algorithms [14], neural networks [15], and fuzzy neural networks [16].

Considerable research has been conducted on load management in microgrids [12], [17]. Much of this work has focused on increasing or decreasing curtailable or deferrable load to keep up with varying generation in microgrids, particularly from renewable resources. Future deployment of "smart appliances" in "smart homes" will contribute to development of further analytics in load management.

5) Flexible Modes

When a microgrid separates from the grid, it is no longer obligated to operate at grid frequency. In some instances, if both sources and loads fundamentally use dc, a microgrid can switch to dc operation under off-grid conditions. Alternatively, of conditions allow, it may be able to adjust its frequency so that transmission components operate at surge impedance. References [18]–[20] describe approaches to controlling such standalone systems.

B. Abnormal Operation

1) Faults

Traditional protection schemes in distribution systems prove inadequate when these distribution systems evolve into microgrids. Protection systems for microgrid should, at the very least, take the following into account: (a) bidirectional flow in feeders; (b) looped feeders; (c) reduced fault levels in islanded operation [21]. Several schemes, such as pilot protection-based [22] and system observer-based [23] methods have been proposed, but this is another important area of research.

2) *Restoration*

An intelligent microgrid should be able to recover automatically in the event of a fault. References [24], [25] describe approaches that can be used to achieve this automatic restoration, also called “self-healing”. Both methods use the smart-grid functionalities, i.e., the “cyber layer” or communication and control layer; [24] uses a decision-based approach while [25] uses an optimization-based formulation.

C. Control and Stability

Control and Stability analysis of cyber-physical systems can be quite complex and challenging; in smart microgrids it can be even more so, due to the diversity of components. Modeling of intermittent and energy-limited resources, storage resources, and power electronic interfaces requires the development of analytics that are quite different from those used in traditional power systems. Ref. [26] reports some work on developing such models and using them to simulate the transient behavior of a microgrid. Ref. [27] reports some noteworthy research on distributed control of a microgid, while taking into account the discrete nature of the signals in a cyber-physical microgrid and their inherent time delays.

IV. CONCLUSION

This paper described present trends, and future needs and directions for research that will drive the realization of smart microgrids. It discussed cited some recent research on these topics, as well as older models and methods that can potentially find new application in this domain. Since this is an emerging field, the discussion was representative rather than comprehensive. It is hoped that this discussion will pave the way for further research in this important area.

V. REFERENCES

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VI. BIOGRAPHY

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