Smart Grid Control: Opportunities and Research Challenges a Decentralized Stochastic Control Approach

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Abstract Recent challenges in power system stability and operation are due to the fact that these complex systems have not evolved in a way to deal with new forms of power generation and load types. Although the grid of the twenty-first century known as “Smart Grid” uses technologies such as two-way communication, advanced sensors, computer-based remote control, and automation, it does not adequately consider increased use of renewable energy which is becoming a major component of the power grid. Moreover, the potential for instability caused by increased frequency deviation and energy imbalance due to high penetration of Renewable Energy Sources (RES) places major constraints on their usage. Therefore, finding a solution to improve the stability of power systems with high penetration of Renewable Energy (RE) is a major challenge that needs to be addressed.

One of the key challenges of the electric power grid of the future is the management of a decentralized power system that includes multiple Distributed Energy Resources (DER) with high usage of uncertain energy sources. In fact, proliferation of microgrids (μGrid) requires utilities to revisit the existing decentralized grid management and its structure. The grid of the future is flexible where both load and generation are stochastic. Therefore, a decentralized stochastic control strategy that is capable of treating the grid as a flexible entity may be a natural solution. In this paper, a description of opportunities and challenges that the grid of the future may encounter is provided. Further, new requirements into the proposed control scheme are considered.

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1 Introduction

The development of human society and its growing economic needs were the catalyst that drove the evolution of transmission grids stage-by-stage, with the aid of innovative technologies. The shortage of fossil fuel energy over the next few decades combined with its potential damage to the environment pushed for large-scale usage of RES. Due to increased penetration of RE, the existing power grid infrastructure faces new challenges in three major areas: policy, pricing, and technology. Although the research opportunity proposed in this paper requires changes in all three areas, the focus is on technology and more specifically control system strategies.

With recent technology advances in energy storage and nonfossil fuel power generation such as fuel cell, the time is ripe to review the existing power grid control structure with key emphasis on balancing between the complexity and stability of this system.

Since the usage of RE is a global priority, intensive research is being conducted on the integration of RES into existing power generation systems. Current research direction can be divided into two main paths:

- Power grid voltage regulation and frequency control with integration of RES, and
- Control of μGrids to satisfy their power exchange and demand.

In both paths, the main objective is stability of the overall grid at the lowest cost. Further, for both research directions, centralized and decentralized control have been considered. Here, we name only a few recent publications in decentralized control. Etemadi et al. [6] consider a decentralized robust control for an islanded multi-DER μGrid. Dagdougui and Sacile [4] proposed a decentralized control of smart μGrid, where each μGrid is modeled as an inventory system locally producing RES. A decentralized stochastic control to maintain power system stability due to increase of RES is proposed by Vrettos et al. [15]. Worthmann et al. [16] compared centralized and decentralized control for a power grid with high integration of DER and distributed battery storage. Di Fazio et al. [5] use decentralized control to improve the voltage profile along the feeder of a distribution system. Kizilkale and Malhame [8] proposed using mean field control theory to manage the coordination and decentralized control of large systems. Authors in [1] also provide an overview of recent publications on distributed and decentralized voltage control of smart distribution networks.

Proposed control strategies in these studies attempt to address challenges of integrating RE to a network originally designed for one-way power flow from generation to the customer. However, considering that 90% of all power outages and disturbances originate in the distribution system [7], it is more desirable to move toward a decentralized grid that allows more flexibility and scalability. It is becoming increasingly apparent that the future of the grid will be "plug and play" [2] with optimized interoperability where μGrids play an essential role. Therefore, the new opportunity from a control theory perspective would be to revisit the grid structure concurrently with the design of the control strategy.

In Sect. 2 of this paper, we first review a grid-integrated μGrid that can provide flexibility, reliability, and resiliency. Then, we define μGrids control system structure and requirements needed for this flexible grid. Furthermore, the concept of *nanogrid* (nGrid) is introduced. In the third section, by recognizing that the grid-integrated μGrids fit the definition of complex systems, we envision a decentralized stochastic control architecture in order to meet the stability and robustness required for this complex system.

2 A Grid-Integrated μGrid

The existing electricity grid is unidirectional by design. It converts only one-third of fuel energy into electricity, without recovering the waste heat. Approximately 8% of its output is lost along transmission lines, while 20% of generation capacity exists to only meet peak demand [2].

Furthermore, the electricity industry landscape is changing due to DER, storage technology, active demand side participation, and a desire for green/renewable energy. Simultaneously, the grid infrastructure is requiring increased investment due to aging in order to maintain resiliency and reliability. These two factors combined (an inefficient grid system and changing industry landscape) create an important and unique opportunity for the control system community by revisiting the 100-year-old structure with the control objective in mind, in order to manage resiliency, reliability, and cost. Therefore, the objective here is not to propose a control strategy for the existing grid but using control theory to provide input for the grid of the future which will be inevitably redesigned. The power industry has already embarked in this path by considering DERs as a viable alternative to centralized generation [14].

The main aspect of this work is to revisit control strategies that were not viable a few years ago due to lack of required technologies. The grid of the future, "Smart Grid", is considered to have adequate sensors, computer networks, and automation in order to make an attempt to revisit its structure. We first make the assumption that residential areas can operate independently from the grid. This means that each house or residential building will have their own μGrid. The residential section of the grid will be completely disconnected from the grid and will be controlled at the household level. We will call these single home μGrids, *nanogrids* (nGrid), which always operate in an island mode and are individually controlled. Every nGrid will have an RE source (i.e., solar), a storage and a sustainable clean energy generator (i.e., fuel cell). If we first focus on a region that the sun is abundantly available, residential RE sources are rooftop solar panels. Solar generations are random. This randomness due to PVs generation that can sell back to the grid and charging demand of Electric Vehicles (EV), combined with unpredictable individual usage is becoming more and more one of the major concerns of utilities. Hence, separation of nGrid from the main grid will help to ease the randomness of the load viewed by the central generation.

Furthermore, we make the assumption that commercial, industrial, university campuses and military locations will form μGrids that can operate in islanded mode and

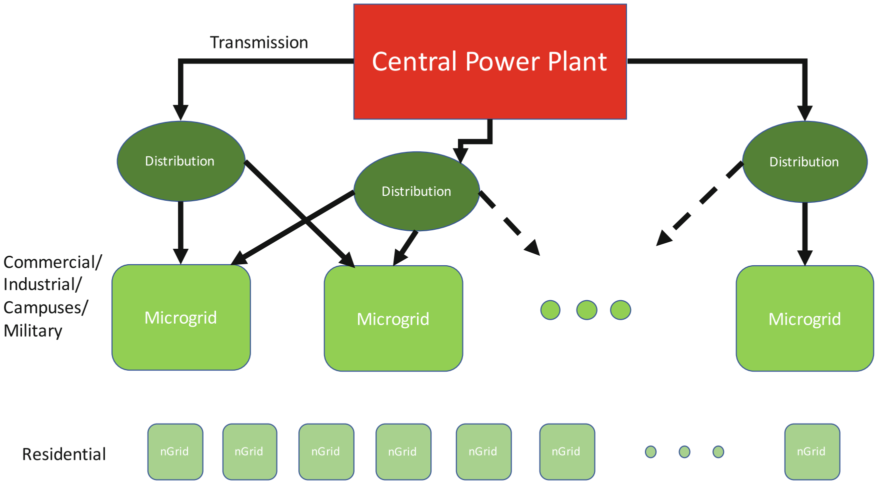

Fig. 1 A simple schematic of the grid of future

connected mode. In this configuration, we forgo the idea of bidirectional transfer of energy between the plant and µGrids. The central power plant will be connected to these µGrids through the distribution centers. Figure 1 presents a schematic description of this idea. In this configuration, central power plants may use intermittent RE sources such as solar farms or controlled RE such as hydro plants. We also assume that no storage is used at the power plant; therefore, energy produced needs to be used by the load. However, storage can be used at distribution centers and µGrids locations.

2.1 µGrids Usage

According to the U.S. Department of Energy (DOE), a µGrid is "a group of interconnected loads and DERs within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A µGrid can connect and disconnect from the grid to enable it to operate either in a grid-connected or island mode". A µGrid is capable of supporting a predefined number of loads but it is typically not designed to operate indefinitely without being connected to the traditional utility infrastructure.

The new generation of µGrids will not only be used for supplying backup power but also a more complex configuration that contains all the essential elements of a large-scale grid such as the ability to balance electrical demand with sources, schedule the dispatch of resources and preserve grid reliability. In fact, these new µGrids will enable increased DERs utilization, limit greenhouse emission, improve local grid reliability, and reduce operating cost. Moreover, driven by declining cost of DERs, μGrids are becoming more appealing for managing the variability of RE [11].

2.2 μGrids Control

In the proposed scenarios, each μGrid needs to be controlled individually. A μGrid controller defined by DOE refers to an advanced control system, comprised of multiple components and subsystems, capable of sensing grid conditions, monitoring and controlling the operation of a μGrid in order to maintain electricity delivery to loads during all μGrid operating modes. Hence, μGrid is a concept for which the control system is the defining and enabling technology [14]. μGrid key control objectives are a seamless transition between islanded and connected mode and load management using local generation and storage for optimized performance. There is ongoing research in this area [3, 9, 10]. Bulk of the research is to design optimal control for μGrids with random generation. When generation does not meet demand, the optimal controller has for objective to connect μGrids back to the grid by minimizing cost. Here, we assume that each μGrid is optimally controlled and meets its objectives when in islanded mode. The challenge is whether the optimality can be maintained when connected back to the main grid. This concept will be explained more in the next section.

3 A Decentralized Stochastic Optimal Control System

For clarity, in this section we use the following definitions:

- Loads: μGrids connected to the grid are central power plant loads,
- Subload: load of each μGrid,
- Generation: central power plant generation,
- Subgeneration: energy sources for each μGrid,
- System: central power plant, transmission, distribution, and μGrids, and
- Subsystem: each μGrid is a subsystem.

For this study, we make the assumption that the grid of the future is a "plug and play" type of grid with the structure proposed in Fig. 1. The proposed grid is a large dynamic system composed of several subsystems. Each μGrid may be connected or disconnected randomly from the grid depending on the load, subload, subgeneration, and generation.

μGrids in this structure will operate by default in islanded mode. It may connect to the grid for two reasons:

- to meet the subload demand in case of insufficient subgeneration, or
- to compensate for overgeneration by the central power plant.

Such on and off participation of the subsystems represent changes in the system structure which may destroy stability and cause the system to collapse. To prevent collapse, systems should be built to have the desirable stability properties that are invariant under structural perturbations [12].

In stabilization of complex systems, decentralized schemes are more practical since perfect knowledge of the interconnections between different subsystems is not required, and the control strategy may guarantee robust stability among the subsystems. That is, closed loop interconnected systems that are stabilized by local feedback laws are connectively stable [13]. Furthermore, when a system is complex, it is difficult or impossible to obtain partitions by physical reasoning. A systematic method which can be used to decompose the system by extracting information from subsystems is required [17].

Decentralized control is an appealing concept for the proposed power grid. It offers an essential reduction in communication requirements without significant loss of performance. Each subsystem is controlled on the basis of locally available information, seldom connecting to other μGrids. The control objective is to stabilize each disconnected μGrid using a stochastic optimal control and at the same time, ensure that the stability and optimality are retained when each μGrid has to connect back to the grid. Therefore, the challenge resides in two parts:

- design a robust control strategy to maintain stability and
- reevaluate system requirements in order to maintain optimality.

Furthermore, in complex dynamic systems, achieving optimality is complicated by the presence of uncertainties in the interconnections among the subsystems. For this reason, the focus will be first on stability via a robust control strategy, optimality will be addressed consequently.

In the past, much of the effort of robust decentralized control strategies was directed toward offsetting the effects of load variations in the system [17]. However, with the emergence of intermittent RE, the problem of robust control has taken on additional significance and complexity, necessitating the use of stochastic models. This is largely due to the fact that in a stochastic environment, the operating conditions become difficult to anticipate. Under such circumstances, it is important to develop robust decentralized control strategies that can protect the system against random disturbances.

One of the primary concerns in large-scale decentralized stochastic systems is the control system robustness. It has been recognized that the degree of robustness required in a high-performance design cannot be achieved by application of existing control practices. For this reason, there has been considerable effort to develop new control schemes with some form of "built in" robustness enhancement [13, 17]. The main objective is to provide a control structure, which ensures that the system performs satisfactorily under faulty conditions. Here, faulty conditions are not viewed as equipment faults, but rather as a consequence of insufficient amounts of power production due to the inherent stochasticity of the generation.

New insights into decentralized control strategies are needed. The stochastic nature of the problem and high demands on quality of service for users make this challenging. To address this problem, it is essential to create:

- adequate methods for analysis of networked systems of high complexity with stochastic inputs for decentralized control, and
- a fundamental theoretical framework and effective methodology for designing optimal robust control schemes for complex decentralized stochastic systems.

The first part requires to evaluate computational challenges associated with the scale of the problem and to model sections of loads and generations as stochastic processes. The second part entails evaluation of multilevel control structures. Further, to address optimality, appropriate optimization techniques need to be considered.

Accomplishment of these aims is expected to provide a model and a decentralized control strategy for complex power systems that take into account variable and intermittent RES.

Satisfactory decentralized design of a system with intermittent inputs will be used to design a control strategy that minimizes the cost of operation and improves stability of the grid.

4 Summary

The grid of today uses technologies such as two-way communication, advanced sensors, computer-based remote control, and automation. It also faces the challenge of increased use of renewable energy. The use of renewable energy sources can reduce greenhouse gas emissions and dependence on fossil fuels. The main problem of installations based on renewable energy is that electricity generation cannot be fully forecasted and may not follow the trend of actual energy demand.

There has been significant interest in deployment of μGrid in the last few years. Also, based on type of customers, applications, and connections, control objectives are different. Therefore, we separated the power grid load into two categories μGrid and nGrid. This paradigm shift will address the concern of load variation due to large numbers of PVs, plug-in electric vehicles, and home storage systems. Furthermore, the direction proposed is a decentralized stochastic control strategy for complex power systems that takes into account variable and intermittent RES with a redefined load.

The opportunity available now to the control community to play a key role in shaping the grid of the twenty-first century is unprecedented. We hope with this effort to bring the attention of this community to the redesign of the system where utility companies are fully aware of the difficulties involved in transitioning their infrastructure, organizations, and processes towards an uncertain future due to DER and RE.

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