Synchronized and Democratized Smart Grids To Underpin
The Third Industrial Revolution
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Abstract: Power systems are going through a paradigm change. Centralized large generating facilities are being replaced with millions of widely dispersed, incompatible, non-synchronous and relatively small renewable or alternative power plants, plug-in EVs, and energy storage units. Moreover, the majority of loads are expected to actively regulate system stability as well. This paradigm change, called the democratization of power systems, is comparable to the great historical event of personal computers replacing mainframes in the technology domain or republics replacing monarchies in the political domain. In this paper, some concepts and principles in politics are borrowed to study power systems. The term synchronized and democratized smart grid (in short, SYNDEM) is coined and the most fundamental features of a democratized society, i.e., the rule of law and the legal equality, are established for SYNDEM. The synchronization mechanism of synchronous machines is identified as the natural rule of law to govern SYNDEM and the legal equality is achieved via operating power electronic converters as virtual synchronous machines (VSM) to homogenize all heterogeneous players. Then, a lateral system architecture is presented to implement SYNDEM. This actually offers a technical solution to realize the lateral power to underpin The Third Industrial Revolution envisioned by Jeremy Rifkin. As a result, all active players in a grid, large or small, conventional or renewable, supplying or consuming, can equally and laterally regulate the grid in a synchronous manner to enhance the stability, scalability, operability, reliability, security and resiliency of future power systems. Live discussions and future updates on this subject are available via joining the LinkedIn group at https://www.linkedin.com/groups/7061909.

Keywords: Synchronized and democratized smart grid (SYNDEM), democratization of power systems, grid architecture, grid modernization, renewable energy, distributed energy resources (DER), lateral power, The Third Industrial Revolution, virtual synchronous machines (VSM), synchronverter, self-synchronization, robust droop control, universal droop control, phase-locked loops

1. INTRODUCTION

Electrification is the greatest engineering achievement of the 20th century (National Academy of Engineering, 2000) and the power system is regarded as the largest and most complex machine engineered by humankind (Kundur, 1994). The power system of a country is part of its most important infrastructure, as “energy regimes shape the nature of civilizations—how they are organized, how the fruits of commerce and trade are distributed, how political power is exercised, and how social relations are conducted” (Rifkin, 2011).

The generation of electricity is currently dominated by centralized large facilities and the system stability is maintained by regulating a small number of large generators to meet the balance between generation and demand. Most loads in the system do not actively take part in system regulation. But now, the landscape of power systems is rapidly changing.

Due to civilization and economic development, the demand for electricity is constantly growing and even reaching the limits of growth (Meadows et al., 1972, 2004), leading directly to supply issues and environmental crisis. The large-scale utilization of distributed energy resources (DER), including renewables, electric vehicles and energy storage systems, is regarded as a promising means for lessening these problems and making the planet sustainable (Rifkin, 2011; Zhong and Hornik, 2013). As a result, power systems are transitioning from centralized generation to distributed generation. Moreover, most loads that do not contribute to the regulation of system stability at the moment are expected to take part in system regulation as well, although mainly on the ON/OFF basis nowadays (Costanzo et al., 2012). It would be much better if the majority of loads are able to take an active role in maintaining system stability in a continuous way, like generators. Such loads are often called active or flexible loads. As a result, the current centralized control paradigm is no longer feasible for power systems with many relatively small generators and flexible loads, together called players in this paper. Adding a communication and information network into power systems, hence the birth of smart grids, has emerged as a potential solution to make power systems more efficient, more resilient to threats, and friendlier to the environment (Amin and Wollenberg, 2005; Amin, 2008). However, this does not solve the problem of how these generators and flexible loads interact with the grid at the physical level. What is even worse is that this could lead to serious concerns about reliability if their operation has to rely on the communication infrastructure at the low-level controls (Overman et al., 2011; Eder-Neuhauser et al., 2016). If the communication network
breaks down then the whole power system could crash. Moreover, when the number of players reaches a certain level, how to manage the communication network is itself a challenge. While it is obvious that a communication network brings many benefits to the operation and management of power systems, there is a need to specify its boundary, with the role specified.

While the above-mentioned challenges are more obvious for the public electric grid, similar problems are also emerging in other power systems, e.g., shipboard power systems (Wang et al., 2015), vehicular power systems (Emadi et al., 2006) and aircraft power systems (Emadi and Ehsani, 2000).

The number of active players in a power system is rapidly growing and could easily reach millions, even hundreds of millions. Understanding the fundamental mechanisms and architecture to govern the stability and operation of future power systems at different scales is a challenging systems engineering problem (Strasser et al., 2015). The seeking for a solution to this problem has been ongoing for years. The FREEDM system envisions to operate power systems as “Energy Internet” or “Internet of Energy” (Huang et al., 2011). An integrated smart grid system is proposed in (Kezunovic et al., 2012) to advocate a synergy of computing and physical resources and envision a trustworthy middle-ware providing services to grid applications through message passing and transactions. A lateral architecture is proposed in (Zhong, 2013b, 2017a,b) to unify the integration and interaction of all active players with the grid. The Intergrid proposed in (Boroyevich et al., 2013) adopts the hierarchical nanogrid→microgrid→...→grid structure to achieve dynamic decoupling of generation, distribution, and consumption by using bidirectional power electronic converters as energy control centers. The Integrated Grid (EPRI, 2014) is proposed to integrate DER in the planning and operation of the grid and to expand its scope to include DER operation.

What is happening in power systems has caught the attention of some visionary social and political thinkers. President Hans-Gert Pöttering of the European Parliament says that “this is no Utopia, no futuristic vision: in twenty-five years’ time, we will be able to construct each building as its own ‘mini power station’ producing clean and renewable energy for its own needs, with the surplus being made available for other purposes.” Jeremy Rifkin calls it the transition from hierarchical to lateral power in his book The Third Industrial Revolution (Rifkin, 2011) and stresses that the lateral power will have the same kind of transformative effect on society as the steam power and the printing press first had, followed by electric power and television. John Farrell calls it the democratization of the electric system (Farrell, 2011). Power systems are going through a paradigm change from centralized control of a small number of large generators to democratized interaction of a large number of relatively small generators and flexible loads.

In this paper, some concepts and principles in politics are borrowed to study the paradigm change of power systems, leading to a complete theoretical framework of synchronized and democratized smart grids (SYNDEM), covering the concept, fundamentals, system architecture and technical routes for future power systems. This actually provides a technical solution to realize the lateral power envisioned in (Rifkin, 2011).

2. SYNDEM CONCEPT AND ITS FUNDAMENTALS

As described above, the democratization of power systems is steadily ongoing. However, an important fact in a democratized society, i.e., individuals can have different or even divisive opinions (Brennan, 2016), should not be ignored. If the democratization of power systems is to be implemented, it is vital to guarantee that all players would synchronize with each other for a common goal, i.e., to maintain system stability. Hence, democratized power systems should be synchronized as well. The term synchronized and democratized smart grids (SYNDEM) is coined here to reflect this.

Democracy is a political concept that empowers all eligible individuals to play an equal role in decision-making. Rule of law and legal equality are the most fundamental features of a democratized society. The rule of law implies that every individual is subject to the law and the legal equality implies that all individuals are equal. In order to realize SYNDEM, it is vital for all active players, large or small, conventional or renewable, supplying or consuming, to play an equal role in regulating system stability and to follow the same rule of law.

2.1 SYNDEM Rule of Law — Synchronization Mechanism of Synchronous Machines

There are different power plants, such as coal-fired power plants, nuclear power plants and hydro power plants in current power systems. However, the electricity generation is dominated by only one type of electrical machines, i.e., synchronous machines, because of their intrinsic synchronization capability. Actually, synchronous machines are mathematically equivalent to an enhanced phase-locked loop called the sinusoid-locked loop (Zhong and Hornik, 2013; Zhong and Nguyen, 2012).

The synchronization mechanism of synchronous machines is the mechanism that has underpinned and facilitated the organic growth and stable operation of power systems for over 100 years. In order to guarantee the compatibility of millions of heterogeneous players with the grid, this mechanism should be followed and adopted as the rule of law for SYNDEM. In this way, the synchronization mechanism also guarantees that all individuals synchronize with each other to reach a consensus, i.e., for the voltage and the frequency to stay around the rated values respectively, e.g. 230 voltage and 50 Hz in Europe and 110V and 60 Hz in the US, so that the system stability is maintained. Moreover, this can be achieved without relying on a dedicated communication network at the low level. The function of communication is achieved based on the inherent synchronization mechanism of synchronous machines through the electricity network. As a result, the communication system in a smart grid can be released from low-level controls and adopted to focus on high-level functions, e.g. information monitoring and management, electricity market etc.

As a matter of fact, the tendency to synchronize, or to act simultaneously, is probably the most mysterious and pervasive phenomenon in the nature, from orchestra to GPS, from pacemakers to superconductors, from biological systems to communication networks (Strogatz, 2004). It has intrigued some of the most brilliant minds of the 20th century, including Albert Einstein, Richard Feynman, and Norbert Wiener. Hence, adopting the synchronization mechanism of synchronous machines as the rule of law to govern SYNDEM is probably the most natural option.
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