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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

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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.

2.2 SYNDEM Legal Equality — Homogenizing Heterogeneous Players

After identifying the rule of law to govern SYNDEM, the challenge lies in the feasibility of homogenizing conventional large generators, relatively small distributed generators and flexible loads and empowering them with the same rule of law — the synchronization mechanism of synchronous machines.

According to the US Electric Power Research Institute, although there are many different loads, there are four main load types: motors that consume over 50% of electricity, Internet devices that consume over 10% of electricity, lighting devices that consume about 20%, and other loads that consume the rest 20% of electricity. It is well known that the adoption of variable-speed motor drives, which are equipped with power electronic rectifiers to convert AC electricity into DC electricity at the front-end, is able to significantly improve the efficiency of motor applications (Bose, 2009). Hence, the 50% of electricity consumed by motors could actually be consumed by power electronic rectifiers. Internet devices consume DC electricity so the 10% of electricity consumed by Internet devices is consumed by power electronic rectifiers as well. As to lighting devices, there is a clear trend in the lighting market to adopt LED lights, which also include power electronic rectifiers at the front end too. Hence, in the future, the majority of electricity will be consumed by rectifiers, whatever the end function is.

On the supply side, most distributed energy resources (DER) are connected to the grid through power electronic inverters. For example, wind turbines generate more electricity at variable speeds, which means the electricity generated is not compatible with the grid and power electronic converters are needed to control the generation and interaction with the grid. Solar panels generate DC electricity, which needs to be converted into AC electricity to make it compatible with the grid as well. Similarly, electric vehicles and energy storage systems require power electronic converters to interact with the grid, too.

In transmission and distribution networks, more and more power electronic converters, such as HVDC (high-voltage DC) links (Arrillaga, 2008) and FACTS (flexible AC transmission systems) devices (Hingorani and Gyugyi, 1999), are being added to electronically, rather than mechanically, control future power systems (Hingorani, 1988), in order to reduce power losses and improve controllability.

Hence, future power systems will be power electronics-based, instead of electric machines-based, with a huge number of relatively small and non-synchronous players at the supply side, inside the network and at the demand side (Zhong, 2017a). Although these players are heterogeneous, they are all integrated with the transmission and distribution network through power electronic converters that convert electricity between AC and DC. If all these power electronic converters could be controlled to behave in the same way, then millions of heterogeneous players could be homogenized and equalized (in the sense of per unit, i.e., in proportion to the capacity), achieving the legal equality for SYNDEM. Even better, if these converters could be controlled to behave like synchronous machines, then they would possess the intrinsic synchronization mechanism of synchronous machines as well. Such converters are called virtual synchronous machines (VSM), or cyber synchronous machines (CSM) as coined in *(Zhong, 2017a)*.

3. ARCHITECTURE

After homogenizing all heterogeneous players to achieve legal equality and equipping them with the synchronization mechanism of synchronous machines (SM) as the rule of law, the SYNDEM architecture can be obtained as shown in Fig. 1 (Zhong, 2017a,b). This allows all conventional power plants, including coal-fired, hydro and nuclear power plants, to be integrated to the transmission and distribution network through SM as normally done without major changes. At the same time, all DER that need power electronic inverters to interface with the grid are controlled to behave as virtual synchronous machines (VSM), more specifically, as virtual synchronous generators, to interact with the grid and all loads that have rectifiers at the front-end are controlled to behave as virtual synchronous machines (VSM), more specifically, as virtual synchronous motors. For HVDC links, the power electronic converters at both ends are controlled as VSM, one as a virtual synchronous generator and the other as a virtual synchronous motor, as well. This presents a unified, harmonized and scalable architecture for SYNDEM.

In such a power system, all power electronics-based players, at the supply side, inside the network and at the demand side, are empowered to actively regulate system stability in the same way as conventional power plants do, unlike in current power systems where only a small number of large generators regulate the system stability. Hence, this architecture is able to achieve the paradigm change of power systems from *centralized control* to *democratized interaction*. Because the synchronization mechanism of SM are inherently embedded inside all the active players, they autonomously interact with each other via exchanging power through the electricity network. This paves the way for the autonomous operation of power systems, which means minimal human intervention is needed to maintain system operation within the designed frequency and voltage boundaries. For example, when a coal-fired power plant is tripped off, the system frequency drops. All SM/VSM that take part in the autonomous regulation of system stability on the supply side would quickly and autonomously respond to the frequency drop and increase the power output in order to balance the power shortage. At the same time, all VSM that take part in the autonomous regulation of system stability on the demand side would autonomously decrease power consumption to balance the power shortage. As a result, the frequency drop is reduced, which helps reduce the number of loads to be tripped off. If a new power balance cannot be reached after all generators reach the maximum capacity then some VSM that serve non-critical loads would further reduce the power intake till new power balance is reached. Similarly, if a heavy load is turned off, all SM/VSM that take part in the autonomous regulation of system stability on the supply side would quickly and autonomously reduce the power output and all VSM that can take part in the autonomous regulation of system stability on the demand side would autonomously increase power consumption to help reach new power balance. The increase or decrease of load power can be of short term or long term, depending on the types and functions of loads. Similarly, the variability of DERs can be taken care of by the players as well.

It is worth emphasizing that all the SM and VSM have the same intrinsic synchronization mechanism so there is no need to rely on additional communication network to achieve low-level control. In other words, the communication network can

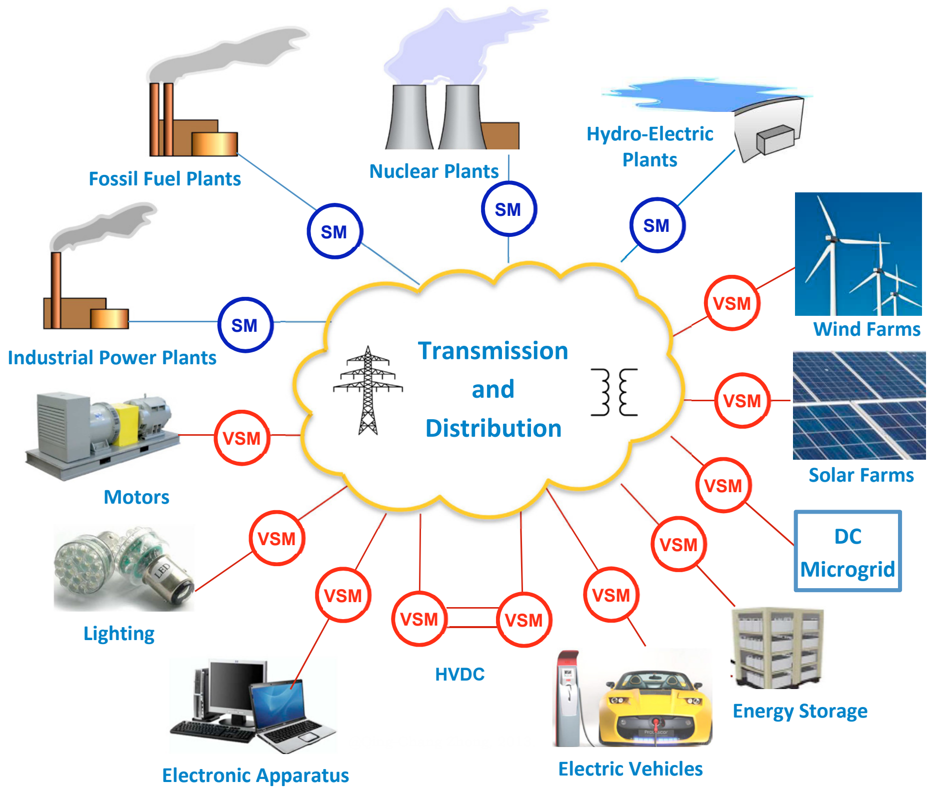

Fig. 1. The lateral system architecture for synchronized and democratized smart grids (SYNDEM) based on the synchronization mechanism of synchronous machines (Zhong, 2017a,b), which offers a technical solution to realize the lateral power that underpins the third industrial revolution as envisioned in (Rifkin, 2011).

be released from low-level control to focus on high-level functions of power systems, e.g. SCADA and market operations (Wu et al., 2005). This also helps enhance the cybersecurity of the system because no access to low-level controllers is provided for potential malicious attackers. It is worth highlighting that this architecture turns all players into active and responsible players to maintain system stability and achieves continuous demand response. This prevents some customers from suffering complete loss of electricity. Instead, all players make a small, often negligible, amount of contributions, which improves quality of service (QoS). Because the synchronization mechanism of synchronous machines is the key principle that has underpinned the growth and operation of power systems for over 100 years, the transition from today's grid into tomorrow's SYNDEM can be achieved gradually.

This architecture is scalable and can be applied to power systems at different scales, from single-node systems to million-node systems, for vehicles, aircraft and public grids. When there is a need, small systems can be connected together. If a part of the system is faulty, then it can be disconnected; after the fault is cleared, it can be re-connected. If HVDC links are used to link AC systems operated at different frequencies, then the AC systems can be operated together as one system or, if needed, as independent systems. Hence, while the architecture allows small grids to merge and form large-scale electricity grids, it also naturally allows large grids to break into small ones. Hence, this may offer the technical foundation to turn a recent move in China that broke up the Chinese Southern AC grid (Fairley, 2016) into a trend worldwide.

This architecture is lateral rather than hierarchical, realizing the lateral power envisioned in (Rifkin, 2011). This empowers all players to directly take part in the regulation of system stability, which enhances system autonomy (Anderson and Brown, 2010) and is consistent with the worldwide trend of increasing autonomy and declining hierarchy (Friedman, 2005; Moore, 2011).

The implementation of the SYNDEM architecture depends on the flexibility of power systems in generation and consumption, which is not a problem. Indeed, power systems worldwide are designed to be very flexible. For example, the UK Grid Code (National Grid, 2016) dictates that the system frequency shall be controlled within the limits of 49.5~50.5 Hz, i.e, $\pm 1\%$ around the nominal frequency, and that generators and apparatus should be capable of operating continuously when the system frequency is within 49.0~51.0 Hz, i.e., $\pm 2\%$ around the nominal frequency. For a 2% frequency droop slope, a 0.5 Hz change of frequency is equivalent to having additional reserve at the level of 50% of the system capacity. Moreover, the SYNDEM architecture is able to release the inertia in wind turbines and large motors etc., which further increases the system inertia. If the reserve/inertia is still not enough, energy storage systems can be added. It is worth highlighting that the fast reaction of power electronic converters could reduce the required level of inertia. Hence, it is envisioned that the flexibility of SYNDEM is not a problem. Similarly for the voltage, the normal operating range for voltage is $\pm 5\%$ for 400 kV and $\pm 10\%$ for 275 kV and 132 kV in the UK. There is plenty of flexibility in reactive power and voltage. The SYNDEM architecture is able to release the full potential of the flexibility already in power systems.

4. TECHNICAL ROUTES

4.1 Based on the Synchronverter Technology

Different options to implement VSMs have been proposed in the literature. The VISMA approach (Beck and Hesse, 2007; Chen et al., 2011) controls the inverter current to follow the current reference generated according to the mathematical model of synchronous machines, which makes inverters behave like controlled current sources. Since power systems are dominated by voltage sources, this may bring detrimental impact, in particular, on system stability (Sun, 2011; Dong et al., 2013; Wen et al., 2015). The approach proposed in (Gao and Iravani, 2008) follows the mathematical model of SM but it requires the measurement of the grid frequency, which is often problematic in practice (Dong et al., 2015). The approach proposed in (Karimi-Ghartemani et al., 2016; Karimi-Ghartemani, 2015) controls the voltage with integrated synchronization but it also requires the measurement or estimation of the grid frequency for the real power-frequency droop control. Although the estimation of the grid frequency is technically not a problem, it should be avoided if possible. The synchronverter approach (Zhong and Weiss, 2009, 2011; Zhong et al., 2014) directly embeds the mathematical model of synchronous machines into the controller to control the voltage generated without the need of measuring the grid frequency or the need of having a dedicated synchronization unit to achieve synchronization (Zhong et al., 2014). The synchronverter has the simplest structure with the lowest number of control parameters among all available options today and has been further developed for microrgrids (Ashabani and Mohamed, 2012), HVDC applications (Aouini et al., 2016; Dong et al., 2016), STATCOM (Nguyen et al., 2012), PV inverters (Ming and Zhong, 2014), wind power (Zhong et al., 2015), motor drives (Zhong, 2013a), and rectifiers (Ma et al., 2012; Zhong et al., 2012), illustrating a complete technical route to implement SYNDEM. This technical route is outlined in (Zhong, 2017a), with full details available in (Zhong, 2017b).

4.2 Based on the Robust Droop Control Technology

In (Zhong and Boroyevich, 2013, 2016), it has been shown that a droop controller structurally resembles an enhanced phase-locked loop. Hence, it also has the intrinsic synchronization mechanism of synchronous machines and can be a potential candidate for implementing VSM. Moreover, the robust droop controller (Zhong, 2013c), initially proposed for R-inverters to achieve accurate power sharing and tight voltage regulation, has recently been proven to be universal and applicable to inverters with output impedance having an impedance angle between $-\frac{\pi}{2}$ rad and $\frac{\pi}{2}$ rad (Zhong and Zeng, 2016). Furthermore, it can be equipped with the self-synchronization mechanism mentioned above without a PLL (Zhong et al., 2016). Hence, the robust droop controller offers another, actually better, technical route to implement SYNDEM. This technical route is outlined in (Zhong, 2017a) as well, with full details available in (Zhong, 2017b).

5. CONCLUSIONS

In this paper, the concept of synchronized and democratized smart grids (SYNDEM) has been proposed and the most fundamental features of a democratized society, i.e., the rule of law and the legal equality, have been established for SYNDEM. The synchronization mechanism of conventional synchronous machines, which has underpinned the growth and operation of power systems for over 100 years, has been identified as the natural rule of law to govern SYNDEM. Moreover, the legal equality of SYNDEM has been established via controlling power electronic converters that integrate heterogeneous DER and flexible loads with the grid to behave like virtual synchronous machines (VSM). Then, a unified, scalable and harmonized system architecture has been presented for SYNDEM. This is a lateral architecture that facilitates autonomy. Two technical routes, one based on the synchronverter technology and the other based on the robust droop control technology, have been pointed out to implement SYNDEM. As a result, a technical solution has been proposed to realize the lateral power envisioned in (Rifkin, 2011), which empowers all players to actively, responsibly and equally regulate the grid in a synchronous manner to enhance its stability, scalability, operability, reliability, security and resiliency.

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