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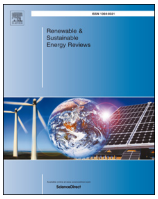

Future power transmission: Visions, technologies and challenges

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ABSTRACT

Power transmission systems are called upon to play a crucial role in the future decarbonized, electrified and digital energy sectors, as they constitute the most effective way of distributing vast amounts of electricity from renewable energy sources to faraway locations. This paper aims at critically reviewing worldwide the regional visions, as well as existing and newer technologies involved in the development and upgrading of bulk transmission systems. The main emphasis is put on the major challenges and boundary conditions arising during the paradigm change that electric energy systems will undergo over the next half century. Recent research and pilot projects on this subject are revised, embracing effective combinations of AC and DC technologies, such as high-voltage AC transmission systems, phase-shifting transformers, flexible AC transmission systems and point-to-point and multi-terminal high-voltage DC systems. The challenges faced by this transition involve technical, economical, environmental, regulatory and social factors that will finally determine the preference for one or another technology in particular regions of the world. General recommendations and guidelines are proposed to increase the probability of success of future transmission projects, regardless of the type of technology, geographic location or particular external conditions. Several somewhat competing architectures are envisioned in this more volatile context, all together offering great possibilities to increase transmission capability while loop flows are prevented and system stability is preserved or enhanced.

1. Introduction

Society is becoming more and more concerned about the need to decarbonize the energy sector, which requires getting rid of fossil fuels quickly and increasing the amount of energy coming from renewable sources (RES). The most recent exhibit of this concern is the 2015 UN Climate Change Conference in Paris, where the representatives of 196 attending parties have negotiated the first legally binding agreement to start a coordinated process aimed at reducing the potential harmful effects of climate change [1]. As a contribution to the Conference of the Parties 21 (COP 21), the International Energy Agency (IEA) has made recommendations to transform today's power systems into networks which are consistent with global climate change goals, highlighting the urgency of implementing emerging technologies in this transitional period to reconcile climate and energy needs [2].

The integration of increasingly higher levels of RES into existing power systems will lead to newer and more acute problems, such as less mechanical inertia, less synchronizing power and frequency regulation capability, and more frequent and abrupt gradients of net load due to the uncertainty and intermittent nature of RES. Solutions for these emerging issues will be based on three main pillars:

- More sophisticated and smarter control centers based on innovative information and communications technologies, both at transmission and distribution levels (cyber-physical systems).
- Ubiquitous deployment of flexible AC transmission systems (FACTS), high-voltage direct current (HVDC) connections and storage devices throughout the system.
- Longer, more powerful, resilient and more efficient transmission grids.

This paper is aimed at reviewing the major steps that are being taken to develop the bulk transmission system of the future, focusing on the visions and technologies that are expected to win in the course of this paradigm change. The elements that should be more valued to achieve an effective grid transition, from technical, economic, operational, environmental and social perspectives, can be identified by highlighting the strengths and weaknesses of the involved technologies.

The relentless and already not so slow growth of renewable generation, both embedded within the heart of urban areas (distributed) and lumped in peripheral areas of many regions worldwide, is being hindered by limitations of the transmission infrastructure. As an example of this, the European Network of Transmission System Operators for Electricity (ENTSO-E) has identified in Europe some main grid

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bottlenecks by 2040 [3,4]. Among the several proposals envisioned by policy makers, lobbyists and researchers, the so-called *supergrid* concept [5–7] stands out as one of the best candidates to duly transform present transmission systems into future hybrid systems characterized by three balanced objectives: sustainability, competitiveness and security of supply.

The paper is organized as follows: Section 2 provides a brief historical perspective of both AC and DC transmission technologies. It is illustrated how, for decades, the AC/DC transmission devices evolved to overcome the diverse static and dynamic constraints derived from the need to safely and efficiently transmit greater amounts of energy at greater distances. Section 3 presents the objectives and topologies behind the *supergrid* concept. There is a growing interest in the benefits potentially brought about by supergrids and constraints that will emerge in the transition from traditional networks to emerging grids. Sections 4 and 5 summarize the main features of the most promising AC and DC transmission technologies, respectively. In Section 6 an appraisal of the technologies considered in previous sections is presented. Section 7 overviews regional visions supported by recent and future major transmission projects, while Section 8 presents the challenges for transmission systems regarding the integration of two predominant renewable sources: wind and solar. Section 9 discusses the trade-offs of different upgrading strategies and technologies in a particular interconnection case. Recommendations for future project proposals and feasibility studies are suggested in Section 10. Finally, Section 11 concludes with the main contributions derived from this review.

2. First milestones

2.1. AC transmission

The evolution of what can be properly termed AC transmission initiated in 1911 with the commissioning of the 110 kV line between Lauchhammer and Riesa, Germany. Since then, AC rated voltages for transmission systems have steadily increased up to the ultra-high voltage (UHV) level of 1200 kV [8–10].

Technically, the utilization of AC transmission lines is limited by static and dynamic system phenomena such as thermal limits, voltage stability or transient stability. Besides resorting to sophisticated conductor arrangements, those limitations were traditionally addressed through the installation of fixed or mechanically switched (shunt or series) capacitors, reactors and synchronous condensers. However, these devices suffer from inherent slow responses and their mechanical components are susceptible to wear and tear. To overcome these problems, the era of FACTS was triggered in the 1950s with the development of the thyristor [11].

The concept of transmission series compensation was first implemented at the 220 kV level in Sweden and simultaneously in the USA [12]. In 1954, the first 400 kV transmission line in Sweden became the first series-compensated installation of the world, allowing power transmission over almost 1000 km [11]. Late in the 80's, the world's first 800 kV series compensator was installed in Brazil [11].

The first shunt compensator in the world was also installed in Sweden, in the 1970s. It consisted of a static VAR compensator (SVC) with thyristor-switched capacitor (TSC) technology [11,13]. In 1980, the first SVC for 500 kV was installed in China, and the first SVC for 735 kV was installed in Canada, in 1983 [11]. As seen, FACTS evolved from SVC to become a reliable alternative for the improved performance of AC systems, and its benefits were soon recognized worldwide for transmission over long distances [13,14].

Another major limitation intrinsically associated with AC systems is that of “loop flows”, namely the impossibility of sending a net amount of power specifically through a given link in a meshed AC system without affecting the power flows of parallel branches, which are exclusively determined by Kirchhoff's laws. This was evident since the early days of interconnected power systems, particularly in huge multi-area systems, such as in Europe and North America, which soon called for the introduction of phase-shifting transformers (PSTs) as a way of partly alleviating this problem [15]. For over 60 years, PSTs have been commissioned worldwide and play a key role in adding certain levels of flexibility to otherwise rigid AC systems [16,17].

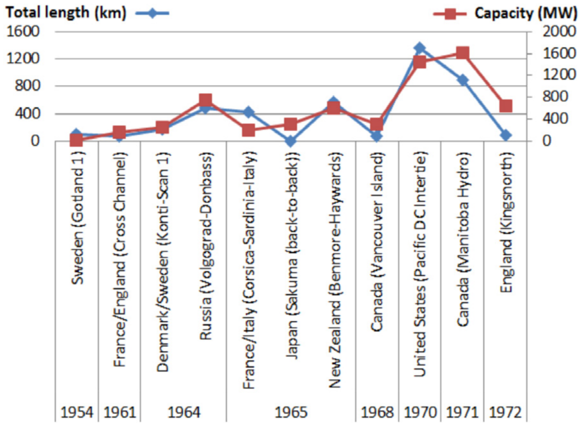

Fig. 1. First HVDC projects (mercury-arc valve based) [adapted from [18]].

2.2. DC transmission

Gotland 1 stands out as the most significant heritage site in the development of HVDC technology. This project was commissioned in 1954, becoming the first commercial HVDC link in the world [11]. It was rated for 20 MW, 100 kV, and consisted of 98 km of submarine cable between Swedish mainland and Gotland Island [18]. Much later, in 1970, the Pacific DC Intertie in the USA was distinguished for proving the advantages of HVDC bulk power transmission (1440 MW) over long distances (1362 km of overhead lines) [18].

The need to build longer lines to transmit larger amounts of power was evident, as shown in Fig. 1. It presents eleven HVDC projects, all based on mercury-arc valves, commissioned worldwide between 1954 and 1972 [18]. Most of those valves were later replaced by thyristors, although others remained in service alongside the newer ones. After 47 years, the HVDC Inter-Island link in New Zealand became the last HVDC system in the world with mercury-arc valve converters in operational service [19]. Thyristor-based valves allow reaching to reach higher powers and voltages, while improving the reliability of the system. In 1997 a new HVDC converter, based on insulated-gate bipolar transistors (IGBTs) instead of thyristors, was demonstrated by ABB. Two years later this so-called voltage source converter (VSC) was commercially introduced for Gotland [18].

Today, the development of both thyristor and IGBT valves has contributed to an important large-scale commercial deployment of HVDC projects. Multi-terminal HVDC (MTDC) technology is also under permanent improvement since 1990, when the Sandy Pond HVDC station in the USA opened as the first bipole MTDC system in the world, where three stations are interconnected and operate under a common master control system [20].

3. The supergrid concept

The supergrid concept was born as a solution to allow large-scale electrical power exchanges over continent-wide areas. This concept, generally associated with DC technologies, has been considered both a potential solution to transmission bottlenecks and an opportunity to trade higher volumes of electricity across longer distances.

If we deem the supergrid basically as a juxtaposition of interconnected yet independent transmission networks, its main objective will be to optimize the added value gained from the integrated system operation, when compared to the benefits achieved by independently