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A Technological Roadmap for the Development of the European Supergrid

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SUMMARY

This paper provides a review of the "state of the art" of the key technologies required for a High Voltage Direct Current (HVDC) Supergrid and proposes a roadmap for the future development of the grid. The Supergrid roadmap has been divided into three phases, Phase 1 2015 – 2020, Phase 2 2020 – 2025 and Phase 3 after 2025. Many Voltage Source Converter (VSC) HVDC schemes are now being commissioned, both for interconnectors, embedded links and for off-shore wind farms, and some of these schemes may form the genesis of the future Supergrid. The development of VSC technology, in terms of increased power ratings and enhanced functionality is a key feature of the roadmap. Similarly cable technology, to deliver higher power ratings at higher operating voltages will be a key driver in the ability to interconnect the nodes of the Supergrid. Conversion of existing AC transmission circuits to DC will enable higher power corridors to be achieved, without changing the environmental impact on the landscape or creating any adverse impacts on human populations. Communication technologies plus control and protection systems will also play a key role in the development of the grid. Many other technologies, such as Full Bridge type Modular Multi-level Converters (MMC), DC circuit breakers, DC to DC converters, power flow control devices, and DC Gas Insulated Switchgear (GIS) will be essential to create a functioning Supergrid and the paper will consider the maturity of their development and will place their entrance into the market on the anticipated timeline embodied in the roadmap.

A continental Supergrid will be essential to enable individual countries to achieve their specific carbon reduction targets, by providing access to remote Renewable Energy Sources (RES), while maintaining security of supply, due to the increased interconnectivity with adjacent networks. It will also provide the technical mechanism for a single European electricity market, allowing trading of energy between countries to provide overall benefits to consumers as well as connectivity to markets outside Europe.

KEYWORDS

Supergrid, roadmap, technology, HVDC, Renewable Energy Sources, VSC,

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1 INTRODUCTION

Electricity consumers in Europe would benefit directly and significantly from a secure supply to the rapid and widespread deployment of RES. To achieve this will require the development of a more interconnected electricity grid to complement the existing national infrastructures. This is referred to as the “Supergrid”. The dispersed nature of many RES in relation to the major European load centres provides further incentive to consider such a Supergrid to be based primarily on the use of HVDC technology. As Direct Current (DC) power transmission is not limited by distance, as is the case for Alternating Current (AC) technology, the remote nature of many RES, such as wind power in the North Sea and solar power around the Mediterranean Sea is no impediment when considering the creation of a Supergrid. The technical challenges inherent in the development of a Supergrid are being studied by a number of organisations, including the Friends of the Supergrid (FOSG). This is an organisation comprising experts drawn from HVDC manufacturers, Cable manufacturers, Transmission System Operators (TSO), Project Developers, Consultants, Legal and Logistics companies. The authors are members of the FOSG Technological Working Group and together they provide a consolidated view of the existing technology base and the future developments which will be required to implement a Supergrid. Since 2012 the FOSG has published an annual report [1] on the “roadmap” to the Supergrid, which considers technological developments in different phases, starting from the Preparation Phase (up to 2015), Phase 1 (2015 – 2020), Phase 2 (2020 – 2025) and Phase 3 (beyond 2025).

Although the Supergrid represents a considerable technological challenge, which is the subject of this paper, other aspects such as the regulatory environment, the permitting process and the attractiveness of the investment conditions will play a major role in determining when and if the Supergrid is constructed. Perceived social benefits of such a Supergrid would be the creation of a single competitive European energy market, which will foster economic welfare, the creation of highly skilled jobs and the strengthening of the role of Europe as a technology leader.

2 SUPERGRID CONCEPTS

Conceptually the Supergrid vision is a pan-continental grid, which would connect all unsynchronized networks of Europe today, e.g. continental Europe, British Isles and Ireland, Nordpool, and the Baltic states. It would also stretch and interconnect to neighbours across borders, e.g. Iceland, Northern Africa, grids further to the east and south-east. Furthermore, the Supergrid would connect power sources in the North Sea and other off-shore hubs. As such it would enable a huge increase in trading capacity, fast balancing of intermittent renewable power, sharing of back-up power and better security of supply. While this is similar to the benefits of the present large 400 kV AC grids of Europe that have developed over the last half century there are some differences, for instance:

1. Much larger interconnection capacity
2. Much longer distance between connection points
3. Agreements between more than two grid operators
4. Mainly the use of HVDC. For HVDC Grids, VSC-HVDC will be the preferred option.

As concluded by CIGRÉ, e.g. the report from the B4-52 working group on HVDC Grids feasibility study [2], the technologies to build such a grid are or will be available in the relevant time frame. FOSG’s Roadmap report has documented the progress of the technologies to fulfil the requirements of the development phases, to initialise and start building the Supergrid. It can be concluded that so far, technology progress is fast, predictable and consistent with estimated time-lines.

The Supergrid will not be built to a blueprint, but rather will develop over time, starting from the most needed and economically attractive interconnections. As the density of such HVDC links increases, it will make sense to gradually connect them in various schemes on the DC and AC side. Already in 2015, Voltage Source Converter (VSC) HVDC links can be designed to meet the largest AC transmission capacities, ranging from 1,400 to 2,000 MW. Line Commutated Converter (LCC) HVDC is available up to 11,000 MW. Recent developments in Cross-linked Polyethylene (XLPE) cable technologies and off-shore wind connections prove that the industry is prepared for the next phases of the Supergrid development; see Figure 1 and Figure 2.

Figure 1. a) The 700 MW, 500 kV Skagerrak VSC-HVDC converter station connecting Danish wind with Norwegian Hydropower. [Copyright ABB] b) The 864 MW off-shore VSC-HVDC platform Sylwin Alpha after installation [Copyright TenneT]

Figure 2 .a) Cross-section of a 525 kV extruded XLPE DC Cable. b) Type testing of the same cable in a cable system with joints and terminations [Copyright ABB]

3 PREPARATION PHASE; UP TO 2015

The period to the end of 2015 has been characterised by a progressive shift of HVDC technology from LCC to VSC, driven by the greater functionality offered by VSC and the increasing levels of power and voltage available. However, LCC schemes are still being ordered outside Europe, where scheme power levels are normally higher and distances considerably longer. The initial driver for this change was the need to connect large far off-shore wind power schemes in the German North Sea and scheme ratings have increased from 400MW at ±150kV to 900MW at ±320kV in recent years. A total of 7 off-shore HVDC schemes are under construction or in operation, all of which are point to point schemes. Additional interconnectors and embedded links using VSC technology are in construction with ratings up to 1000MW at ±320kV. The France – Spain connection uses 2 x 1000MW VSC links to greatly increase the power transfer capacity to the Iberian Peninsula. In China, two multi-terminal VSC-HVDC schemes have been commissioned. The 3 – terminal Nan'ao scheme (400/100/50MW at ±150kV) entered service in late 2014, with a 4th terminal (50MW) planned for a later stage [3]. This scheme has demonstrated multi-vendor operation, with three Chinese manufacturers supplying converter stations. The 5 – terminal Zhoushan (400/300/100/100/100MW at ±200V) was commissioned in early 2015. Multi-terminal control strategies have been developed for both of these schemes, where one “master” station controls the DC voltage and all other stations control the local power in-feed [4]. These schemes operate with a single protection zone, i.e. any fault on the DC transmission system will be cleared by opening of all of the AC circuit breakers.

In anticipation of the needs of a Supergrid, a number of manufacturers [5, 6, 7] have developed hybrid DC circuit breakers, using a combination of power electronics and mechanical isolation. These systems are presently under test to prove their operational characteristics, particularly their ability to interrupt rapid rates of rise of fault current and achieve circuit isolation within 5ms from fault initiation. Full Bridge type MMC is also able to interrupt DC faults and may find application for VSC Overhead Transmission Line (OHTL) projects and multi-terminal HVDC systems.

The first 600kV submarine cable scheme is presently under construction in the United Kingdom, using LCC technology rated at 2200MW. To withstand the high dielectric stress a Mass Impregnated (MI) cable using Polypropylene Laminated paper (PPLP) insulation is used. This scheme is due to enter commercial service in 2017. XLPE cables tested to 500kV and 525kV have been announced by Japanese and European manufacturers, although none is yet on order.

4 PHASE 1; 2015 – 2020

Operational experience of MMC VSC point to point schemes and the commissioning of the first multi-terminal schemes in China will provide the stimulus to design schemes which are enabled for multi-terminal operations. The 2 x 720MW South – West scheme in Sweden and the 800/1200MW Caithness – Moray scheme in the UK are examples of schemes which have anticipatory designs for multi-terminal operation. The rationales for such schemes are improved interconnectivity between neighbouring networks and the evacuation of remote RES.

Many schemes commissioned in this Phase will be rated at 1000MW and ±320kV, which becomes a “de facto” standard, although not a technological limit. As 500kV VSC technology has been proven at the Skaggerak 4 scheme during the preparatory Phase, bi-pole schemes of up to 1600MW could be anticipated during Phase 1. Increased ratings of IGBT devices, up to 2000A should be generally available from multiple vendors, allowing scheme powers to reach 2000MW and above, if converters are connected in parallel.

Mass impregnated (MI) cables using Polypropylene Laminated Paper (PPLP) insulation will be in service at 600kV allowing scheme powers to reach 2200MW. Such cables can operate at an insulation temperature of 80°C and present conservative design margins may allow higher power ratings without increasing the cross-sectional area of the central core. XLPE cables at 500kV, in development and testing to CIGRÉ recommendations during the Preparation Phase, will be available for project implementation. Such cables are able to operate at higher temperatures, up to 90°C, providing the optimum utilisation of the core material. Operational experience at 320kV and later at 500kV will be essential to prove the reliability of such high power and high voltage schemes, before further steps in power or voltage can be considered.

Gas Insulated Lines for HVDC (DC GIL) are expected to become available for transmission voltages up to 500kV as an option for complementing overhead lines in areas where underground transmission is required.

5 PHASE 2; 2020 – 2025

It is anticipated that this Phase will be characterised by the continuation of the system integration process which was initiated in Phase 1, laying the foundations for a European-wide overlay grid. A key driver for this phase of the Supergrid development will be the need to increase interconnectivity in line with EU targets, which have a benchmark of achieving 10% interconnectivity by 2020. [8] These figures are expressed as a percentage of the production capacity of the member states.

The increasing DC voltages and hence power transmission levels which occur in Phase 1 will continue in Phase 2, to match the needs for increased interconnectivity and evacuation of bulk power from RES. VSC-HVDC converter technology is anticipated to increase up to 600kV and routinely be implemented in bi-polar configurations. This will allow power transfers of up to about 2.5GW in single bi-polar scheme. Power levels beyond this will be achievable by parallel connection of converters. The advent of improved semi-conductor devices may also contribute to this development. Higher voltages can be achieved by connecting more devices in series, but higher current, say in excess of 2000A per device, would be of greater benefit in achieving higher power levels per converter station. IGBT devices consist of a great number of parallel connected chips and in principle the number can be increased or devices connected in parallel. The use of parallel converters, although adding significantly to station costs, may become a more attractive option to achieve high power transfer levels, where the loss of one large pole (say about 1.25GW or even more) may be economically and technically unacceptable for AC grid operation.

Submarine and underground DC cables will represent the key technology interconnecting the nodes of the Supergrid. By Phase 2 it is anticipated that MI-PPL cables will be available for DC voltage up to 600kV and slightly above, to continue towards matching the present capability of Overhead Transmission Lines. The use of XLPE cables will continue to be seen as a more economically and environmentally attractive option compared with MI/MI-PPL cable, due to the market needs and capability of production units for such cables. Service experience for XLPE cables will get better during this phase, mostly for 320 kV level. Although in Phase 1 there are already extruded cables rated for >500kV available, indicating that during Phase 2 there will be at least one cable section at voltage levels >320 kV under installation or in service. Cables rated >500 kV already in use in Phase 1 will drive continued R&D in the field of extruded plastic insulation, by using more advanced techniques with further material development to control electrical stress distribution, for example using nanotechnologies etc. between the high voltage core and the outer grounded screen. This should allow XLPE cables to become available at voltage levels in excess of 600kV during Phase 2. Figure 3 illustrates this trend.

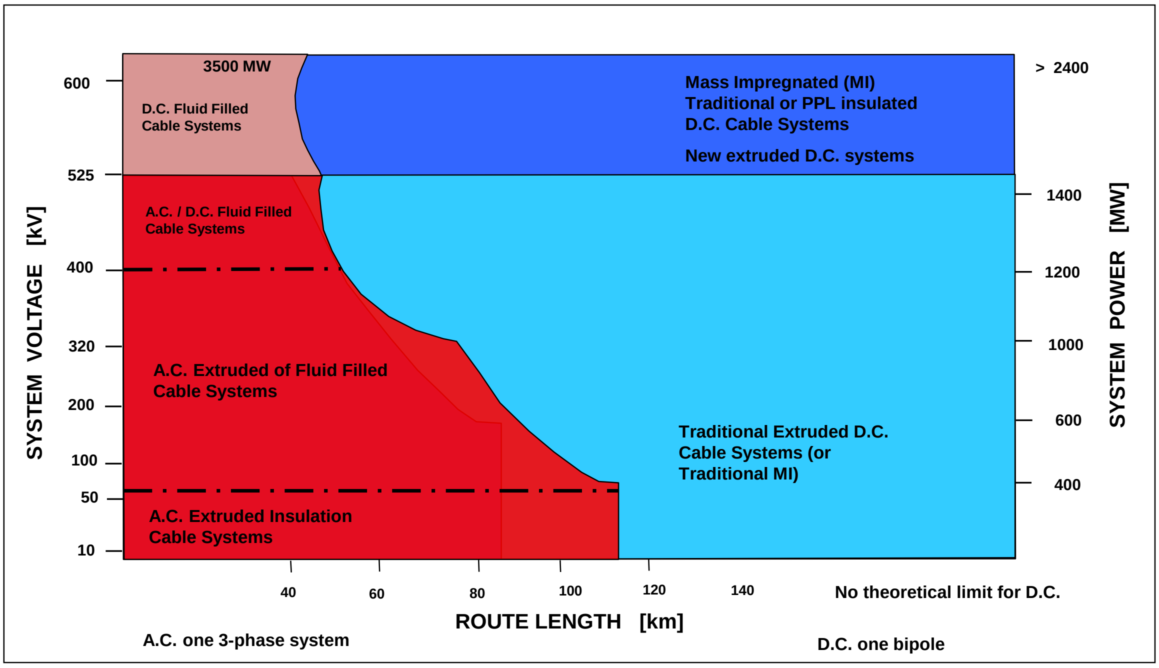

Figure 3 AC and DC cable capabilities

HVDC OHTL will find application to relieve congestion in the existing AC networks. The planning of new OHTL corridors has to take into account technical aspects, i.e. the contribution to maintain the security of supply, as well as environmental aspects. Depending on the existing network structures, using existing AC corridors can be an interesting option. This could include the conversion of existing double circuit AC lines (2 x 3 phase HV conductors) to double bi-pole lines (2 x 2 pole HV lines + neutral conductor). Although HVDC OHTL technology is presently at ±800kV and will have reached ±1100kV by Phase 2, it is anticipated that applications in Europe would be restricted to ±500kV, based on the power transmission needs and the adverse environmental impact of towers using a higher voltage.

6 PHASE 3; AFTER 2025

The Supergrid may evolve during Phase 3 from the aggregation of disparate point to point links and multi-terminal systems, but this will be difficult without some degree of coordination, even if no overall “architect” exists to design the grid. Some schemes will require a degree of anticipatory investment to make them compatible with future connection to a grid. National network operators and regulators and pan-European organisations such as the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Agency for the Cooperation of Energy Regulators (ACER) will need to create the regulatory framework in which a Supergrid can evolve during Phase 3.

During Phase 1 and 2 the progressive increase of the power and voltage of HVDC schemes will be accompanied by periods of consolidation to gain operational experience of the new technologies. By Phase 3 it is anticipated that MI-PPLP cables >600kV and XPLE cables >525kV will be in routine service. This will allow high power corridors >2GW for VSC and >3GW for LCC to be in common use to provide the “back bone” of the Supergrid. Any limits on the power levels achieved may relate to the ability of the interconnected AC systems to withstand the loss of power in-feed, rather than any technological barrier imposed by the HVDC technology. The control and protection systems developed for multi-terminal systems in Phase 1 and 2 will be deployed for the emerging Supergrid. The work of CIGRÉ, the European Committee for Electro-technical Standardization (CENELEC) and other organisations will have provided the basis for robust control and protection systems, which ensure the interoperability of equipment provided by multiple vendors. Advanced technologies, such as DC/DC converters, developed in Phase 1 and demonstrated in Phase 2, will become available as a “building block” for the Supergrid in Phase 3. Niche technologies, such as superconducting cables may find application in places where OHTL or conventional cable solutions are not viable, for example short distance, high power corridors in urban areas, where available land is at a premium.

7 ROUTE TO THE SUPERGRID

HVDC systems are going to play the key role in the development of the Supergrid. The development of HVDC links in Europe has experienced a significant boost at the beginning of the current century by planning more and more individual HVDC links interconnecting different synchronous zones in Europe or connecting large scale off-shore wind parks. In recent years, the first HVDC systems strengthening existing synchronous AC networks went into the detailed planning.

Most of the systems existing or in the detailed planning today have just two connection points to the AC systems; they are also referred to as point-to-point links. These links are typically tailored to individual customer requirements and designed by individual manufacturers. However, as the number of HVDC systems grows, their becoming interconnected on the DC side forming so-called HVDC Grid Systems is expected to bring significant benefits, such as higher operational flexibility, higher security of supply or increased utilisation of the corresponding transmission corridors.

The step from separate HVDC links to HVDC Grid Systems involving several TSOs and having various vendors for systems and equipment brings challenges for all players in the market. Binding requirements and regulations for the power system design and operation as defined in Network Codes (NC) as well as commonly agreed technical guidelines and operating principles, as defined in Technical Standards, are pre-requisites for the practical implementation of HVDC Grid Systems.

The challenges in the fields of regulation and standardization are tackled on a European level by the ENTSO-E and CENELEC. The two organizations closely cooperate as is demonstrated by ENTSO-E's working group "Standardisation" and CENELEC's Technical Committee (TC) 8X/ Working Group (WG) 06 "System Aspects of HVDC Grids", working together based on the Memorandum of Understanding between ENTSO-E and CEN/CENELEC [9].

ENTSO-E's Network Code for HVDC and DC connected Power Park Modules (NC HVDC) [10] is of particular importance for planning and designing HVDC systems, in that it defines binding rules for HVDC transmission at their connecting points to the European AC grids. The rules at the AC connection points will consequentially determine rules for designing and operating future HVDC Grid Systems; however such rules are not yet part of the NC. These topics are addressed by CENELEC TC 8X/WG 06 [11]. Since HVDC Grid Systems are a completely new field of technology, the WG in a first step elaborates Functional Specifications, which are intended to support HVDC Grid System planning, tendering, constructing and operation involving several TSOs and several vendors of equipment, systems and sub-systems. The WG 06 bases its work on the findings of related CIGRÉ working groups and liaison partnerships have been established with CIGRÉ working groups that are currently active. These are WGs B4.56 (DC grid codes), B4.57 (Models for HVDC converters [12]), B4.58 (Load flow control), B4.59 (Control and protection), B4.60 (Reliability and availability), and B4/C1.65 (Recommended voltages for DC grids).

At the time of writing this paper the NC HVDC has been recommended by the ACER for adoption to the European Commission. The WG 06 is currently preparing a release of the first parts of the Functional Specification for circulation inside CENELEC as a Document for Comments (DC). Updates of this document are planned on a yearly basis.

In addition to common technical principles, rules and standards, the development of the Supergrid needs to be supported by appropriate regulatory frameworks. This includes developing the conditions for financing the grid infrastructures and supporting free trading of electricity across national borders. Europe's transition to a carbon-free energy supply will be successful only if power can flow without barriers, balancing the discontinuous availability of RES and bridging their distance to the load centres. Solving the technical challenges is on its way and no “showstoppers” have been identified.

8 CONCLUSIONS

The development of a European Supergrid will be a significant challenge and will require that many different technologies are brought to a proven state of implementation by multiple manufacturers within the next few decades. The roadmap concept presented in this paper has provided a vision of what technologies will be required and an indication of the timeline when these technologies are expected to be available. At each stage of development of technology, proven operational experience will be required to ensure that the equipment and systems can achieve high levels of reliability and availability for the Supergrid. Issues related to the interoperability of control and protection systems provided by multiple manufacturers will need to be resolved, but experience from China shows that these are not insuperable problems. Competition between manufacturers provides a natural driver for innovation, to extend the power ratings of equipment and improve their functionality, but centralised coordination of direction and economic support for research and development will be required to make a Supergrid a reality. The authors foresee no fundamental technological barriers to the development of a continental Supergrid, but recognise that there are many challenges in the regulatory and economic areas still to be resolved.

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