21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

272

BOLOGNA 2011

Evolutions and challenges towards a potential Pan-European HVAC/HVDC SuperGrid

G. FULLI, A. PURVINS
European Commission – Joint Research Centre – Institute for Energy
The Netherlands

S. RÜBERG
Technische Universität Dortmund
Germany

A. L'ABBATE, G. MIGLIAVACCA
RSE (Ricerca sul Sistema Energetico)* SpA
Italy

SUMMARY

The European power transmission grid is on the critical path to meet the European Union (EU)'s climate change and energy policy objectives for 2020. This trend is expected to continue also for the years after 2020, in view of ambitious decarbonisation targets by 2050. The main challenge will be the power system integration of very large amounts of variable renewable energy sources (RES), especially wind and also solar, while keeping overall system reliability at acceptable levels, in a liberalised background. To this scope, a more flexible, yet robust, transmission grid is needed. In presence of several issues more frequently constraining the realisation of new High Voltage Alternating Current (HVAC) overhead infrastructures, the need for evolution in the design and operation of transmission system towards a re-engineering process emerges in Europe. Among the different measures to support such shift, there may crucially be the use of High Voltage Direct Current (HVDC) technologies for advanced power transmission.

The present paper, which partially results from the ongoing activities within the European research project REALISEGRID, investigates the role of HVDC towards the development of the future transmission system in Europe: particular attention is paid to current evolutions and challenges ahead of the potential realisation of a pan-European (mixed HVAC and HVDC) SuperGrid in a long term view, also in line with the recently issued European Commission's Energy Infrastructure Package.

After introducing key technical, economic and environmental characteristics of HVDC technologies, this paper reports some specific long-distance HVDC applications for bulk power transmission in extra-European systems towards potential SuperGrid implementations in Europe. The developments at the eastern and southern edges of the European system as well as across the North Seas, the Baltic Sea and the continental network are then specifically investigated in their evolution stages as potential building blocks of a long term pan-European SuperGrid.

KEYWORDS

Electricity highways, European transmission system, HVDC, RES integration, scenarios, SuperGrid.

---

*: Former ERSE, previously CESI RICERCA

Authors' e-mail addresses: Gianluca.FULLI@ec.europa.eu Arturs.PURVINS@ec.europa.eu Sven.Rueberg@tu-dortmund.de Angelo.LAbbate@rse-web.it Gianluigi.Migliavacca@rse-web.it

INTRODUCTION

In the European Union (EU), concerns related to security of energy supply, electricity market restructuring and environmental sustainability crucially drive new trends, which may significantly impact on the design and the operation of the European electricity networks. These are on the critical path to meet the EU's climate change and energy policy objectives for 2020 and beyond, in view of the ambitious 2050 decarbonisation targets [1]. In Europe, there is then a need to start today designing, planning and building the electricity networks of the future, which will largely still be in use around 2050 [2]. Concerning the European transmission network, the challenge will be the power system integration of very large amounts of variable renewable energy sources (RES), especially wind and also solar, while keeping the overall system reliability at acceptable levels, in a liberalised background. To this scope, a more flexible, yet robust, transmission grid is then needed. Furthermore, the ongoing energy market liberalisation process in Europe is leading to the steady rise of inter-area power exchanges, generally increasing the transmission network congestion. To address such issues, the solution of enhancing the power transmission capacity, traditionally realised by adding new High Voltage Alternating Current (HVAC) overhead infrastructures, is nowadays seriously hampered by economic, social and environmental constraints.

Then, the need for evolution in the design and operation of transmission system towards a re-engineering process emerges in Europe: this may then crucially need the use of advanced power transmission devices like High Voltage Direct Current (HVDC) technologies. These represent key elements of potential European electricity 'highways', as introduced in the so-called EC's Energy Infrastructure Package [1]. These highways must be capable of: i) accommodating ever-increasing RES generation in the North and Baltic Seas and in the East and South of Europe and also North Africa; ii) connecting these new generation hubs with major storage capacities; iii) coping with an increasingly flexible and decentralised electricity demand and supply. Such infrastructures needs to be built stepwise, ensuring compatibility with the current grid, based on a modular development plan [1].

Within this context, the present paper aims at investigating the role that HVDC may play towards the development of the future transmission system in Europe: particular attention is paid to the challenges ahead of the potential realisation of the vision of a pan-European (mixed HVAC and HVDC) SuperGrid, constituted by electricity highways, in a long[1] term view (up to 2050 horizon).

This paper, which partially results from the ongoing activities within the European research project REALISEGRID [3], first introduces key technical, economic and environmental characteristics of HVDC technologies. Then, specific HVDC transmission extra-European applications in operation are analysed, focusing on relatively long-distance ties for bulk power transmission towards potential SuperGrid implementations in Europe. The developments at the eastern and southern edges of the European system as well as across the North Sea, the Baltic Sea and the continental network are specifically investigated.

HVDC TRANSMISSION

Technological overview

The first HVDC installations date back to 50ies; nowadays, HVDC technologies are worldwide deployed counting on a long operational experience. In fact, this power electronics-based technology exhibits characteristics that have already made it widely attractive over HVAC transmission for specific applications, such as very long distance power transmission (several hundreds to few thousands kilometres), long submarine cable links and interconnection of asynchronous systems, as well as bulk power transport [4][5][6]: for the latter application, the most recent (currently world record) example has concerned the installation of ±800 kV, 6400 MW HVDC overhead lines (OHLs) in China. Thanks to its quick and flexible response, the HVDC technology can deliver several benefits to the transmission system, such as: transfer capacity enhancement, power flow control, transient stability improvement, power oscillation damping, voltage stability and control, rejection of cascading disturbances. Recent advances in power electronics, related to the availability of fully controllable solid-state components like Gate Turn-Off (GTO) thyristors, Integrated Gate Commutated Thyristors (IGCT) and Insulated Gate Bipolar Transistors (IGBT), coupled with HVDC traditional features, may

---

[1] In this article, short, mid and long term horizons refer to up to 2015, up to 2020, and after 2020 timeframes, respectively.

lead to a further deployment of this technology in European transmission grids. This is the case of the very promising self-commutating (or self-commutated) Voltage Source Converter (VSC)-based HVDC, which represents the state-of-the-art technology for connection of offshore wind farms and for multi-terminal applications. The key advantages of VSC-HVDC with respect to the line-commutated Current Source Converter (CSC)-based HVDC (the classic or conventional HVDC) are the possibility to feed reactive power into a network node and provide a smoother voltage support [4][5][6]. VSC technology is available for two-, three- or multi-level converters. Multi-level VSC is a recent development, requiring less filtering and having lower losses per converter respect to two-level VSC. Table 1 summarizes the key metrics and properties of CSC-HVDC and VSC-HVDC.

Table 1: Summary of key metrics and basic properties of HVDC technologies [4]

System description	**CSC-HVDC**	**VSC-HVDC**
System ratings in operation	±500 kV, 1000 MW (cable)	±200 kV, 400 MW (cable)
	±800 kV, 6400 MW (OHL)	350 kV, 300 MW (OHL)
Future trend of system ratings	towards higher ratings	
Operational experience	> 50 years	~ 10 years
Lifetime	30-40 years	30-40 years(1)
Converter losses (at full load, per converter)	0.5-1%	1-2%
System capabilities		
Transmission capacity	■■■	■■
Power flow control	■■■	■■■
Transient stability	■■	■■■
Voltage stability	■	■■
Power oscillation damping	■■	■■■
Reactive power demand	■■■	■
System perturbation	■■■	■
Reactive power injection possible	no	yes
Easy meshing	no	yes
Limitation in cable line length	no	no
Ability to connect offshore wind farms	no	yes
Investment costs per MW	■■	■■■

Legenda: ■ — Small; ■■ — Medium; ■■■ — Strong; (1) estimated value, not enough experience yet

In general, modern HVDC systems do not only allow for power transmission from one area to another one, but also offer several technical advantages over traditional HVAC transmission systems [4][6]. Some of them are here recalled, also in view of further applications in the European power system:

- Practical absence of transmission line length limitation: HVDC systems can be used as long submarine or underground cable transmission lines with a low level of losses, without the need of reactive compensation, differently from HVAC cable transmission. For this reason, the grid integration of increasing, far-away located RES power plants like offshore wind farms that needs long-distance power transmission through undersea cables sees today the use of HVDC transmission as the most feasible solution.
- Transmission capacity increase: For a given conductor cross section, HVDC transmission can transfer more current through a conductor compared to conventional HVAC transmission. Accordingly, the conversion of existing lines from HVAC to HVDC can increase the transmission capacity on the considered route: this could be very worthwhile in Europe, e.g. for cross-border trade.
- Ability of quick and bi-directional control of power flow: Active power can be transmitted in both directions and quickly reversed if needed. Also, the amount of transmitted active power can be set to a fixed value that is maintained during all operating conditions, especially during the occurrence of faults in neighboring network sections. This avoids the overloading and the consecutive loss of the transmission line. These features of HVDC can improve the stability of the surrounding HVAC power system or even of the total network.
- No increase of short-circuit current at the connection points: HVDC lines can be integrated into a power grid with limited need for upgrade of downstream equipment (e.g. circuit breakers, transformers

etc). In case of short-circuit at one of the terminals of the HVDC transmission line, the converters can be switched off within milliseconds preventing them from contributing to the short-circuit current.
- Interconnection of asynchronously operated power systems: HVDC transmission lines can be used to connect two asynchronously operated power grids in order to provide not only for active power exchange in emergency situations but also for active power cross-border trade. This can either be carried out by a HVDC link between two HVAC substations of two different power grids (full HVDC) or by a back-to-back (B2B) coupling inside one single HVAC substation (back-to-back HVDC).

Economic aspects

Capital expenditures for transmission systems are highly dependent on different parameters, such as technological parameters (type, power rating, operating voltage, etc.), local environmental constraints, geographical characteristics, technology maturity as well as costs for material, manpower and right-of-way. In general, environmental constraints increase costs and implementation time – like e.g. for OHLs – while technological advances in manufacturing usually reduce costs – like e.g. for power electronics components or for XLPE (Cross-Linked Polyethylene Extruded) cables.

In order to take into account all the different factors impacting on assets expenditures, Table 2 reports up-to-date (average) ranges for the costs of different HVDC transmission components in continental Europe in standard installation conditions. In Table 2 HVDC devices for a throughput power ranging between 350 and 3000 MW for HVDC OHL and 1000 MW for HVDC XLPE cables are considered. In the cost range the lower limit (min value) refers to installation costs in European countries with low labor costs, while the upper limit (max value) refers to installation costs in European countries with high labor costs, like e.g. Germany, The Netherlands, or France [4].

It shall be clearly pointed out that the proposed cost ranges represent typical average values and shall not be taken as absolute data. The actual overall project costs may differ from the provided average values if exceptional technological, geographical, and/or environmental circumstances apply.

Table 2: Typical investment cost ranges for selected HVDC transmission system components [4]

System component	Voltage level	Power rating	Cost range		Unit
			min	max	
HVDC OHL, bipolar	±150 - ±500 kV	350 - 3000 MW	300	1000	kEUR/km
HVDC underground cable pair	±350 kV	1000 MW	700	2500	kEUR/km
HVDC undersea cable pair	±350 kV	1000 MW	1000	2000	kEUR/km
HVDC VSC terminal, bipolar	±150 - ±350 kV	350 - 1000 MW	60	125	kEUR/MW
HVDC CSC terminal, bipolar	±350 - ±500 kV	1000 - 3000 MW	75	110	kEUR/MW

Costs for HVDC OHLs refer to the base case, wherein the installation of OHLs over flat landscape and in sparsely populated areas is considered. In this base case, high towers with a large span length can be used which directly results in lower overall installation costs. Costs for installations over hilly and averagely populated land as well as over mountains or densely populated areas are taken into account by a surcharge of +20% and +50%, respectively.

The proposed investment cost ranges for HVDC OHLs include all costs related to the transmission medium (i.e. those ones for equipment, engineering, and installation). The cost ranges provided for HVDC converter equipment are presented "per terminal", wherein a terminal includes all equipment at one side of the bipolar transmission line: both converters, reactive compensation (if needed), active filtering, switchgears, engineering, project planning, taxes etc. except any costs related to the transmission medium. This accommodates the facts that on the one hand a voltage source converter is by nature bipolar and on the other hand that bipolar HVDC installations are preferred within a synchronized power grid for system security reasons [4][7].

Moreover, as an essential part of HVDC-based systems, the transmission medium itself plays an important role in costs saving and environmental fitting. Although the initial investment for an HVDC converter station is higher than the one for an HVAC substation, the investment costs of the overall HVDC transmission system can be lower than those ones of the HVAC transmission system: the cost savings in the transmission line and the absent need for reactive compensation can make up for the higher HVDC station costs if a certain transmission distance is reached (i.e. "break-even" distance). This strongly depends on the specific project parameters: the break-even distance is typically between

80 and 120 km for offshore submarine cable connections, while for onshore applications it can be in the order of 700 km in the European continental system [18].

Environmental impact

The environmental fitting of an electrical power transmission system is of increasing importance. Due to political restrictions and public environmental awareness, environmental considerations have become an important part of approval procedures and project planning. In order to accommodate this circumstance, Table 3 reflects the land use for selected HVDC transmission system components. In case of OHLs the term land use refers to the surface area occupied by the tower footing and the span, while in case of cables this term quantifies the surface area over the underground cable run. For both the span and the surface area of the cable run, the usability is constricted after construction of the line. For HVDC terminals the term land use refers to the area occupied by the facility buildings [4].

Table 3: Typical surface occupation for selected HVDC transmission system components [4]

System component	Voltage level	Power rating	Land use		Unit
			min	max	
HVDC OHL, bipolar	±150 - ±500 kV	350 - 3000 MW	20000	40000	m^2/km
HVDC underground cable	±350 kV	1000 MW	5000	10000	m^2/km
HVDC undersea cable	±350 kV	1000 MW	0		m^2/km
HVDC VSC terminal, bipolar	±150 - ±350 kV	350 - 1000 MW	3000	10000	m^2
HVDC CSC terminal, bipolar	±350 - ±500 kV	1000 - 3000 MW	30000	60000	m^2

HVDC transmission provides a clear environmental advantage over HVAC OHL due to its ability to go underground by the use of HVDC cables. The use of cables minimizes the visual impact of the transmission line since the surface area over the cable run can be re-naturalized with e.g. bushes or shallow root trees, as long as the cable can be made accessible for maintenance or repair purposes at short notice. In case of overhead lines, the width of right-of-way can be significantly reduced by approximately 30 to 50 % when choosing HVDC instead of HVAC transmission; however, HVDC converter stations occupy more space than HVAC substations (even if VSC are more compact than CSC converters).

Furthermore, the electromagnetic field emission of HVDC lines is not pulsating and can be forced to a minimum value in case a dedicated return conductor is used and the conductor arrangement is selected accordingly. The result is a significantly lower electromagnetic pollution compared to the electromagnetic emissions by conventional HVAC transmission, especially when OHLs are used. The acoustic emission of HVDC stations has to be considered but can be reduced to comply with the legal requirements by an indoor station design.

Considering all the aforementioned features, HVDC systems can then provide solutions for a large number of transmission problems that TSOs may be confronted with in their planning process. Naturally, punctual techno-economic and environmental analyses for each specific case have to be carefully carried out [4][8][9][35].

BULK POWER HVDC TRANSMISSION: EXTRA-EUROPEAN EXPERIENCES

Today, existing long-distance[2] HVDC transmission systems worldwide are primarily in use for the bulk power point-to-point interconnection between remote power generation (mainly hydro and thermal and also offshore wind power in the future) and highly urbanized areas (like e.g. Los Angeles, Mumbai, and Shanghai), where additional power support is needed. Furthermore, the main choice reasons for HVDC instead of conventional HVAC transmission consist in the lower transmission losses on the link, environmental advantages (higher power density per ground unit), and the positive impact on the stability of the existing network. Besides, in the case of the interconnection of two asynchronously operated HVAC networks and the interconnection between two HVAC networks with different frequencies, HVDC constitutes the only feasible solution [5]. In addition, the experiences as well as the reliability records underline the feasibility of HVDC for long-distance transmission. For

---

[2] The term "long-distance" refers here to overhead lines with a length longer than 500 km [5].

example, the Tian-Guang[3] HVDC link operated with average energy availability of 92.04% from 2001 to 2007 [10]. Another case is the Square Butte[4] HVDC system characterized by a similar average energy availability value of 90.29% from 1999 to 2008 [11]-[15]. Furthermore, Itaipu 1[5] and Itaipu 2[6] transmission systems have much higher average energy availability of 96.53 and 96.83% respectively in the time period from 2005 to 2008 [14][15].

The average energy availability of the existing HVDC lines as a function of time tends to rise after the first 10 years of operation and remains relatively constant afterwards. The overall average energy availability between 1993 and 2004 is approximately 94.3%[7]. Scheduled energy unavailability increases for the facilities older than 20 years, possibly indicating that a higher level of maintenance is required for older HVDC systems. An amount of approximately two thirds of the total forced energy unavailability of HVDC transmission systems around the world in the time period from 1983 to 2006 is caused by failure in HVAC and/or auxiliary equipment of the HVDC system in service.

Due to the geographical location and other reasons, each of the HVDC OHLs in the following has its own specific features. The Quebec-New England[8] link is a multi-terminal HVDC transmission system with the possibility to supply power from the middle of the line, where additional terminals are located. Besides, Xiangjiaba[9] HVDC link transports 6400 MW (world record at moment, until new ±800 kV, 7200 MW HVDC project is commissioned in 2013) at the highest voltage level of ±800 kV. Furthermore, the Zhengping converter station of the Three Gorges-Changzhou[10] project is exposed to very heavy industrial pollution; therefore, the electrical insulation has to be higher than conventional, all high-potential HVDC equipment is installed indoor, and all the HVDC neutral equipment is installed outdoor. Because of the extreme line length and the difficult logistics along the route, the Inga-Shaba[11] project is composed of two monopolar lines (in contrast to one bipolar line) in electrically parallel connection. The Caprivi[12] Link is the longest system worldwide that uses VSC-HVDC for power transmission in combination with OHLs. The world longest HVDC transmission link planned so far is the Rio Madeira[13] link in Brazil, scheduled for completion in 2012 [5]. Further long-distance HVDC interconnections for bulk power transport are in operation or planned around the

---

[3] This CSC-HVDC OHL (capacity: 1800 MW; voltage: ±500 kV; line distance: 960 km; commissioning year: 2001) transports energy from the hydropower plant Tianshengqiao in South-West China, Yunnan Province, to the load centre of Guangzhou in the Guangdong Province on the South coast of China.

[4] This CSC-HVDC OHL (capacity: 500 MW; voltage: ±250 kV; line distance: 749 km; commissioning year: 1977) transports energy from the Milton R. Young coal-fired power plant situated near Center in North Dakota, USA, to Duluth in Minnesota, USA.

[5] This CSC-HVDC OHL (capacity: 3150 MW; voltage: ±600 kV; line distance: 785 km; commissioning year: 1986) transports energy from one of the world's biggest hydroelectric power plants, Itaipu, on the Parana River to Sao Paulo region, the industrial centre of Brazil.

[6] This CSC-HVDC OHL (capacity: 3150 MW; voltage: ±600 kV; line distance: 805 km; commissioning year: 1987) transports energy from one of the world's biggest hydroelectric power plants, Itaipu, on the Parana River to Sao Paulo region, the industrial centre of Brazil.

[7] Such analysis regards 51 HVDC transmission systems and includes not only long-distance links.

[8] This CSC-HVDC OHL (capacity: 2250 MW; voltage: ±450 kV; line distance: 1480 km; commissioning year: 1990) transports energy from the La Grande II hydro power station, Canada to Montreal, Canada, and Boston, USA.

[9] This CSC-HVDC OHL (capacity: 6400 MW; voltage: ±800 kV; line distance: 2070 km; commissioning year: 2010) transports hydro energy from South-Western China to Shanghai on China's East Coast.

[10] This CSC-HVDC OHL (capacity: 1500 MW; voltage: 500 kV; line distance: 860 km; commissioning year: 2002) transports energy from the Three Gorges hydropower plant in central China to the eastern coastal area of Changzhou city.

[11] This CSC-HVDC OHL (capacity: 560 MW; voltage: ±500 kV; line distance: 1700 km; commissioning year: 1982) interconnects the Inga hydroelectric complex at the mouth of the Congo River to mineral fields in Katanga province (prior Shaba), eastern part of Democratic Republic Congo (former Zaire).

[12] This VSC-HVDC OHL (capacity: 300 MW; voltage: 350 kV; line distance: 950 km; commissioning year: 2010) interconnects the Caprivi Strip in eastern part of Namibia and the Gerus converter station in the middle of Namibia. In its final configuration the Caprivi Link will be a 600 MW bipolar OHL operating at ±350 kV.

[13] This CSC-HVDC OHL (capacity: 3150 MW; voltage: ±600 kV; line distance: 2500 km; scheduled commissioning year: 2012) is planned to connect two hydroelectric power plants on Madeira River in Porto Velho, north-west of Brazil, to Araraquara, Sao Paulo state, south-east coast of Brazil.

world. A particularly fast development in the field of Ultra High Voltage Direct Current (UHVDC) systems is recorded in India and in China, where research and tests are ongoing towards ±1000-1100 kV UHVDC technologies.

In general, from the operational experience of existing HVDC systems, it emerges that HVDC transmission technologies are essential for an efficient long-distance, bulk power transport: its low losses and its smaller environmental impact made it the preferred choice over conventional HVAC transmission. In addition, the experiences gained from the operation of HVDC transmission projects for years and the reliability records presented underline the feasibility and reliability of HVDC for long-distance transmission. HVDC transmission can therefore represent an important option for the necessary upgrade and expansion of the European transmission grid in order to ensure a stable integration of RES in the future [5].

DEVELOPMENTS TOWARDS A POTENTIAL SUPERGRID IN EUROPE

In this section, the goal is to investigate the main current and future evolutions and challenges towards a potential pan-European SuperGrid.

Figure 1 shows the current synchronous areas of the European power system, five of which are now part of the ENTSO-E[14] association, namely the former UCTE (continental Europe network), NORDEL (Nordic countries network), BALTSO (Baltic countries network), UKTSOA (United Kingdom's network), ATSOI (Irish network). It is important to note that, even if BALTSO is now part of ENTSO-E system, it is still synchronously interconnected with the Russian IPS/UPS system.

There exist several full HVDC links in the European power system of ENTSO-E, mainly used for long submarine ties and/or asynchronous systems interconnections. There is currently also an installation of B2B HVDC (between Finland and Russia).

By analysing the ongoing transmission expansion plans in Europe (see also [18]), several HVDC developments emerge, also towards new applications of HVDC technologies in Europe. This is especially the case for: 1) HVDC links embedded into the HVAC synchronised system(s); 2) meshed offshore grids. Concerning application 2), there is a very strong potential for HVDC offshore grids development in Europe [18], especially in the North Seas (see following subsection).

For the applications 1) and 2), VSC-HVDC is the most promising technology over the classic CSC-HVDC. In fact, as seen VSC-HVDC can be very useful both for the connection of remote offshore wind farms to the main power grid and integration into the HVAC synchronised system, since VSC-HVDC does not depend on a specified ESCR (Effective Short Circuit Ratio) or on reactive power support to perform a reliable commutation process. Due to its multi-terminal configuration potential, VSC-HVDC represents then the key technology for building offshore grids. Furthermore, the independency of reactive power support enables VSC-HVDC to perform a black start which may help TSOs to re-energize network sections that suffered from a system blackout. VSC-HVDC can provide additional capacity for the point-to-point power transmission over short- to medium-long distances within a power grid while also providing reactive power support at its terminals. This contributes to power system stability and frees up transmission capacity on neighbouring lines that was formerly occupied by reactive power transmission. In combination with a wide-area monitoring system, the fast modulation of power injection at the HVDC terminals can be also used to damp power oscillations within the power grid and to assure system stability. The first VSC-HVDC embedded interconnection in the European system will be the 2x1000 MW, ±320 kV France-Spain underground link (under construction, due by 2013-2014). This is a clear example where the implementation of a VSC-HVDC has been chosen as a technically and environmentally feasible solution. The aim is to address cross-border congestions (frequently occurring in both directions), enhancing the net transfer capacity while also fostering RES integration and avoiding overloading of the transmission line, with environmental advantages over conventional HVAC OHL transmission. Further embedded VSC-HVDC interconnections planned in the European system are: France-Italy (2x600 MW, ±320 kV, expected by 2016), Norway-Sweden (2x600 MW, ±300 kV, three-terminal, expected by 2014/2017), Italy-Switzerland (2x500 MW, ±400 kV, expected by 2017, merchant). In addition, some embedded CSC-HVDC projects have been also planned, like the two ones in Great Britain (Scotland-England, 1800 MW, 500 kV, expected by 2018, and Scotland-Wales, 2000 MW, 500 kV, expected by 2015) aiming

---

[14] ENTSO-E: European Network of Transmission System Operators for Electricity [17].

at increasing transmission capacity and integrating RES, while overcoming environmental constraints via sea bypasses. There also exist other potential embedded VSC-HVDC links under study (like Belgium-Germany, Austria-Italy) [18].

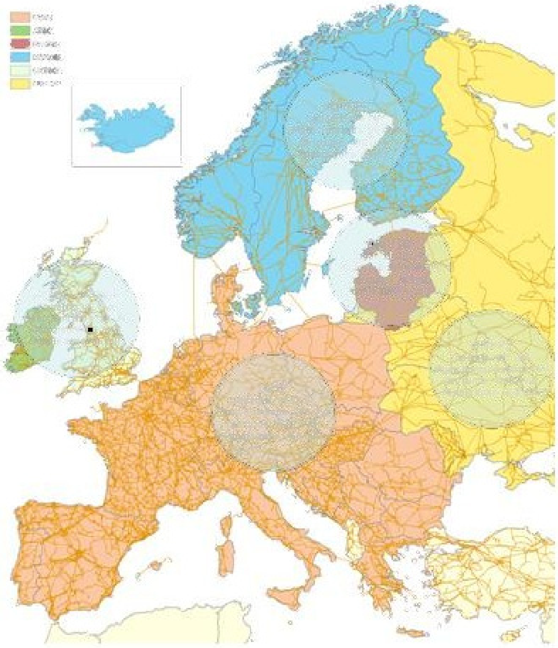

Figure 1: The European synchronous areas ([16])

In the case of bulk power point-to-point transmission (>2000 MW), the choice of which HVDC technology to apply is today limited to CSC-HVDC as the currently available power ratings of VSC-HVDC are still limited. However, in case of CSC-HVDC, if the ESCR of both considered network nodes assumes a low level (lower than 2.0), the grid needs first to be reinforced. On the other hand, in the case of power transmission up to 1200-2000 MW, VSC-HVDC may represent a feasible option which provides higher benefits in both environmental impact and network controllability. The future technological developments of VSC-HVDC towards increased power ratings may allow for considering VSC-HVDC as another option for bulk power transport.

The two types of emerging HVDC applications in Europe as above described may represent the first, essential building blocks of a potential pan-European SuperGrid, as conceived for the purpose of the present paper. Such infrastructure can be also characterised by including an overlay grid, as for example highlighted in [5], based on a potential HVDC backbone infrastructure interconnecting the North Sea countries, and on a North-South axis in Germany transporting North Sea offshore energy to the consumption centres of Northern and Central Europe and storage infrastructure in the Alpine and Nordic regions.

Then, a pan-European SuperGrid can be hereinafter conceptually thought, upon extension of the current European transmission system (which is mainly based on HVAC assets like 220/275/330 kV and 380/400 kV OHLs), as an electricity grid infrastructure based on mixed HVAC/HVDC onshore and offshore backbones (highways), interconnecting RES and storage technologies and transporting bulk power to load centres across the whole European continent and beyond.

In terms of geographical coverage (see also Figure 1), such pan-European SuperGrid, in its potential, long term (after 2030 to 2050) scenario, may include an enlarged HVAC continental network, synchronously interconnecting also Turkey, Baltic countries, Moldova and possibly Ukraine, and further asynchronously interlinked with Scandinavia and British islands, embedding HVDC links and also combining offshore grids, in presence of a closed (by HVAC/HVDC assets) MedRing and interconnections between the shores across the Mediterranean Sea. In this frame, islands like Malta (via HVAC), Cyprus and Iceland (via HVDC) would be electrically linked to such system; Russia (including Kaliningrad enclave) and Belarus would be asynchronously interconnected as well. Such pan-European infrastructure may also include different HVAC transmission technologies[15], like PSTs and innovative devices like FACTS, smart lines and cables (thermally-monitored lines and cables via RTTR/DTR), HTC (HTLS) lines, GILs, HTSCs, in addition to HVDC assets, for RES integration sinergically with storage. The simultaneous presence of several power system controlling devices will also require an advanced coordination, possibly via WAMS. In a longer term, further potential technologies, like 750 kV EHVAC and eventually UHVDC, might be deployed for few specific bulk power transport applications. However, innovative technologies need to be duly tested and carefully evaluated at technological, techno-economic and socio-environmental level [19].

Naturally, it has to be remarked that the realisation of a such potential pan-European SuperGrid is a complex process, as there are still several techno-economic, technological, regulatory, market and socio-environmental issues that will have to be properly handled and solved over the years. Towards this goal, considering the needed re-engineering process and the relevant paradigm shift with respect to the traditional approach to transmission system development and operation adopted so far in Europe, different stages for an incremental evolution from the current European grid are to be foreseen. In this sense, a modular development over the years, especially after 2030, is an essential requisite for a successful implementation of such ambitious plan, as recalled by the EC [1] and by ENTSO-E [20].

To ensure timely integration of renewable generation capacities in Northern and Southern Europe and foster further market integration, the recent so-called Energy Infrastructure Package of the EC [1] identifies four crucial priority corridors of the European power system that will have to be more urgently developed and reinforced. These are (see also Figure 2):

1. Offshore grid in the North Seas and connection to Northern as well as Central Europe
2. Completion of the BEMIP (Baltic Energy Market Interconnection Plan)
3. Interconnections in South Western Europe
4. Connections in Central Eastern and South Eastern Europe

The ongoing and future developments in these four extended macro areas are described in the following subsections.

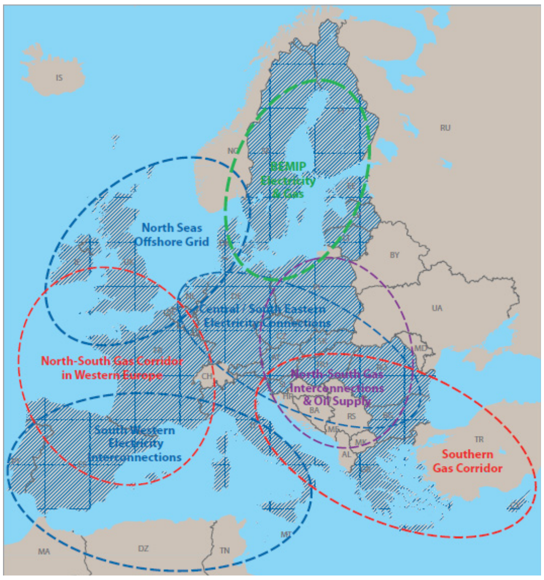

Figure 2: Priority corridors in Europe (source: [1])

North Seas Offshore Grids

A vast potential for offshore (mostly wind) electricity production exists in the North Sea, the Irish Sea and the English Channel (generally called as North Seas). In order to exploit this, the development of a

---

[15] PST: Phase Shifting Transformer; FACTS: Flexible Alternating Current Transmission System; RTTR: Real Time Thermal Rating; DTR: Dynamic Thermal Rating; HTC: High Temperature Conductors; HTLS: High Temperature Low Sag; GIL: Gas Insulated Line; HTSC: High Temperature Superconducting Cable; WAMS: Wide Area Monitoring System; EHVAC: Extra High Voltage Alternating Current.

North Seas offshore infrastructure to jointly interconnect national grids in North-West Europe and integrate the numerous expected offshore power plants would be needed. Current approach to offshore wind generators integration consists in their connection to the mainland via radial schemes. This has worked acceptably for the smaller, near shore installations seen to date, but larger, more distant offshore wind plants have to be integrated differently. An alternative approach is then to plan, develop, build and operate an offshore grid by sharing assets between wind connections and cross-border capability (also via links between wind parks in different countries). The need for this coordinated approach to offshore wind connection is now widely recognised (see e.g. [1][21][22]). Furthermore, such offshore grid would also enhance cross-border electricity trade and exploit the large scale storage of electricity from pumped hydroelectric units (mostly located in Norway), able to level out supply fluctuations typical of variable energy sources, while improving system security, flexibility and robustness for wind evacuation.

Additional benefits from this coordinated offshore infrastructure development would consist in: overall costs decrease; environmental impact reduction; technological standardisation push.

However, on the other hand, several major issues (and to some extent crucial challenges) will have to be addressed ahead of a North Seas offshore grid development. These can be grouped as: 1) technical and technological; 2) economic and financial; 3) regulatory and market. The first group of challenges refers to the choice of grid architecture and technology, where mixed HVAC and HVDC assets are to be used, as pure HVAC transmission would not be feasible, due to the generally long distances involved. Basically, AC transmission can be used within offshore clusters, whereas, depending on the capacity to be transported, classic HVDC or VSC-HVDC can be applied for long distance transmission. Intermediate link between these two sections of the offshore grid is the multi-terminal VSC-HVDC interconnection: this represents the key element of such offshore infrastructure, though it is not yet fully developed and proved. Also, in this frame, the crucial challenge consists in the development of a meshed DC network architecture, with its essential components like breakers, transformers, and control, coordination and protection devices [23]. To address some of these critical issues, the use of functionalities provided by power electronics has been recently highlighted, like in [24], in which it is described that high power DC/DC converters can act as DC transformers, also incorporating the function of DC section fault isolation proper of DC circuit breakers. Costs and losses of such power electronics elements have to be taken into due account.

The second group of challenges refers to the huge investments necessary for building up an offshore infrastructure. Related issues concern the investments financing and burden shares for each involved stakeholder. The third group of challenges relates to the several cross-country issues that need to be duly coordinated and harmonised, like e.g. grid planning, permitting procedures, offshore generators grid connection, RES incentives, market design. All these barriers must be overcome in the due time towards the realisation of a North Seas offshore infrastructure.

Considering all the above reported critical issues, a tight coordination of the involved countries has been made necessary.

In Dec. 2009, the North Seas Countries Offshore Grid Initiative (NSCOGI) was jointly launched by ten nations (Belgium, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, Norway, Sweden, United Kingdom) with the main objective to coordinate the offshore wind and infrastructure developments in the North Seas. It has to be also remarked that onshore reinforcements of the European network, notably in Northern and Central Eastern Europe, will be needed to transmit electricity further inland to the major consumption centres.

Figure 3 shows a possible offshore grid concept as developed in [21]: the existing (in red), planned (in green), commissioned (in pink) and potential (in blue) interconnections in the North Seas and also in the Baltic Sea are evidenced. It can be noticed that the backbones of a North Seas offshore grid are represented by important links like the ones between Norway and Germany (NorGer and NorD.Link), between Norway and Netherlands (NorNed 1 and NorNed 2), between Netherlands and Denmark (Cobra), between United Kingdom and Netherlands (BritNed) as well as the potential ones between United Kingdom, Norway and Germany/Netherlands. Further elements of the future offshore grid may be constituted by the recently commissioned/under construction VSC-HVDC links for offshore wind connection to the German shore, like BorWin 1, BorWin 2, SylWin 1, HelWin 1, DolWin 1 projects. In the Baltic Sea, the HVDC interconnections between East Denmark and Germany at Kriegers Flak are crucial for the area towards offshore wind integration and cross-border trade [18].

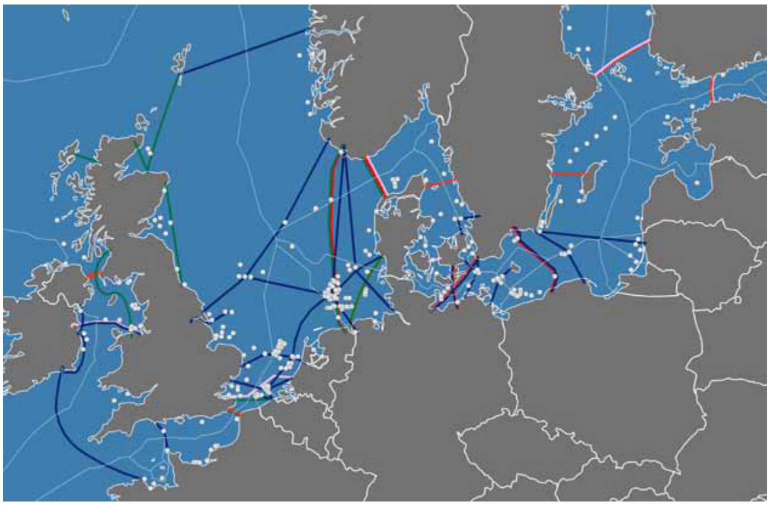

Figure 3: Illustration of a possible offshore grid in the North Seas and the Baltic Sea (source: [21])

BEMIP for electricity

The need for an effective interconnection of the Baltic Sea region was identified over the latest years by the EC as one of the key priority energy infrastructure actions. Under the initiative of the EC, in Jun. 2009, eight Baltic Sea EU Member States (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Sweden) and Norway (as observer) signed a Memorandum of Understanding on the Baltic Energy Market Interconnection Plan (BEMIP), a comprehensive action plan on energy (both electricity and gas) interconnections and market improvement in the Baltic Sea Region. The main objective of BEMIP is to envisage concrete measures to end the relative "energy isolation" of the Baltic States by 2015 and integrate them into the wider EU energy market. In this frame, a crucial goal is the strengthening of the interconnections between the Baltic States and their EU neighbouring countries [25].

Figure 4 shows the existing and the planned interconnections in the Baltic region. The tie between Estonia and Finland, Estlink 1 (VSC-HVDC, 350 MW, in operation since Dec. 2006), is the only interconnection at present between the Baltic States (still synchronously linked with the Russian system IPS/UPS) and the other EU countries. After Estlink 1, ongoing projects like LitPol (interconnecting Lithuania and Poland via HVDC back-to-back, 2x500 MW, to be operational by 2015/2020), NordBalt (interconnecting Sweden and Lithuania via VSC-HVDC, 700 MW, to be operational by 2015-2016), and Estlink 2 (interconnecting Estonia and Finland via CSC-HVDC, 650 MW, to be operational by 2013-2014) are strategic for the Baltic region. After 2020, an additional HVDC interconnection, linking Latvia and Sweden, may be also put in place. Further internal reinforcements, especially in Latvia and in Lithuania, as well as cross-border interconnections between Lithuania and Latvia and between Latvia and Estonia, are also planned in a short-mid term horizon in order to take full benefit of the above three key infrastructures between the Baltic region, on one side, and Scandinavia and continental Europe, on the other side [27].

The most important and critical interconnection project in the Baltic region is the mentioned LitPol.

It has to be noted that Poland, whose network belongs to the European continental one, and Lithuania, part of Baltic grid (see Figure 1), are the only two geographically bordering countries in the EU whose power systems are not interconnected via an electricity link. In order to bridge this gap and close the Baltic Energy Ring between the Lithuanian, Latvian, Estonian, Finnish, Swedish and Polish power systems, a Poland-Lithuania link is then crucial. This will help ensure the operation security and reliability of Baltic power grids, their integration into the common European power market as well as the exploitation of local renewable electricity sources (wind). In addition, a Poland-Lithuania link will help secure power supply for Poland's north-eastern region. All these aspects are expected to play a primary role also taking into account that the nuclear plant of Ignalina (Lithuania), whose generation covered until recently a relevant share of the Baltic electricity consumption, was phased out at the end of 2009. On the other hand, a lack of certainties still concerns the investment project for a new nuclear plant, to be installed at Visaginas (Lithuania) by 2020. The ongoing LitPol link project consists of a 400 kV double circuit HVAC overhead transmission line between Ełk (Poland) and Alytus

(Lithuania), where the transformer substation will be reconstructed and expanded by a HVDC back-to-back converter station. The length of the line will be approximately 154 km. In 2015 the first stage of the project is due with a capacity of the interconnection of 500 MW, while in 2020 the full project capacity of 1000 MW will be available, upon completion of several needed internal reinforcements, especially in the Polish grid [8][18].

After the realisation of LitPol and the other critical projects in the region, further crucial challenge will be the synchronisation of the Baltic grid with the European continental network (not before 2020): this has become a top priority also for the EC energy policy [25]. However, this may firstly require additional system upgrades and extension, before the (eventual) displacement of HVDC back-to-back converter from Alytus substation and the insertion of HVDC back-to-back converters on all interconnections between the Baltic grid and the IPS/UPS system (Russia, Belarus, Kaliningrad region)[16]. Secondly, and crucially, the resolution of this issue will be strongly influenced by the installation of the new nuclear plant at Visaginas, which can facilitate the synchronisation operation of the Baltic grid with the continental Europe system. On the other hand, investment decisions may be impacted also by the simultaneous nuclear plant construction in the close Russian enclave of Kaliningrad (where a 2x1150 MW power station is planned by 2018), while other projects for nuclear installations potentially exist in the region (in Poland and in Belarus). Towards the potential synchronisation of the Baltic grid with the European continental network, a further issue to be solved will concern the "electrical system status" of Kaliningrad region, whether the latter grid were to be kept synchronised with the Baltic system, operated in (partial/total) "islanded mode" or disconnected from the Baltic system (while kept synchronised with IPS/UPS via new dedicated OHLs through Lithuania to Belarus). To evaluate all the options for Baltic synchronisation, a new research study is being launched at ENTSO-E level [18]. Due to the construction of new nuclear plant(s) in the region, the need for further interconnections for cross-border trade may also emerge (after 2020). This concerns the potential links between the Kaliningrad region and Germany (or Sweden) via HVDC undersea cable (600-1000 MW), between the Kaliningrad region and Poland (HVAC OHL with HVDC back-to-back, 600-1000 MW) as well as the reinforcements at the interface between the Kaliningrad region and Lithuania (with a capacity increase of 900 MW) [26].

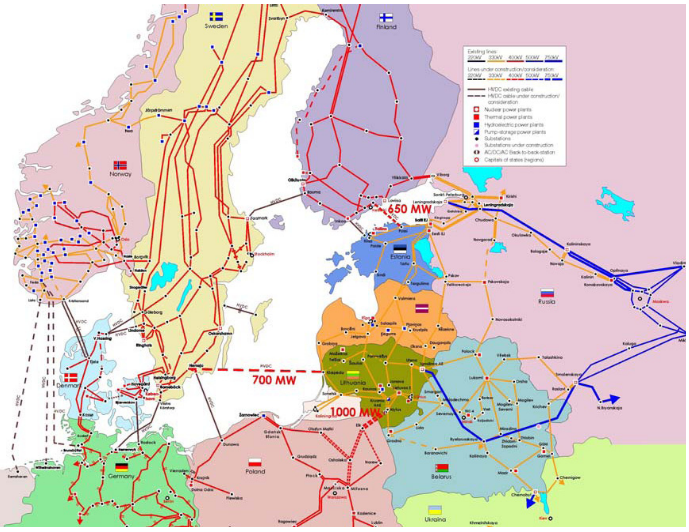

Figure 4: Planned and existing interconnections in the Baltic region (source: [27])

South Western Europe (and Mediterranean Ring)

The South Western Europe is also a crucial area, as France, Italy, Portugal and Spain will host significant future developments of variable renewable electricity generations capacities up to 2020 and beyond. At the same time, the Iberian Peninsula is at moment almost an electric island, as the four links between France and Spain are very frequently congested and additional transfer capacity is urgently needed. The new France-Spain VSC-HVDC interconnection (above mentioned) will increase

---

[16] An alternative option would consist in the opening of one or more of those tie links between the Baltic grid and the Russian IPS/UPS system.

the current interconnection capacity from 1400 MW to about 2600 MW (however, as some congestion might remain even afterwards, the long term target is to increase the capacity to 4000 MW). Other short-mid term plans in the region refer to the reinforcements/new interconnections at the Portugal-Spain and France-Italy interfaces as well as the connection of islands to the continental grid: this is the case of Balearic islands (to be connected to Spanish mainland via a 2x200 MW submarine CSC-HVDC link from Mallorca) and Malta (to be synchronously interconnected to Sicily via a 220 kV, 250 MVA, 120 km ca. long HVAC cable) [18].

Moreover, the South Western European countries play a key role in their interconnecting to North Africa, which could become increasingly important because of its huge potential for solar (and also wind) energy. To this end, the EC fosters the energy interconnections linking the EUMENA (EU, Middle East and North Africa) countries and the closing of the Mediterranean Ring (MedRing) [28].

As of today, there is only one interconnection between the African and the European continent (Morocco-Spain): this is a double circuit HVAC undersea cable with 1430 MVA total capacity, but at present this interconnection cannot be fully exploited (limited to ca. 60% capacity) due to local constraining congestions. Plans exist to increase the transfer capacity on this tie (there may also exist the option to convert the HVAC into HVDC assets).

As it can be seen in Figure 5, four synchronous areas can be currently recognised along the Mediterranean basin: the European continental network, to which north western Maghreb countries (Morocco, Algeria and Tunisia) are synchronously coupled; the system of the interconnected north eastern Maghreb (Libya, Egypt) and Mashreq countries (Jordan, Syria and Lebanon[17]); the system of Israel and Palestinian Territories; the network of Turkey (operated by TEIAS) [29]. Upon completion of ongoing developments, the Turkish system is to be fully synchronised with the European continental network (expected by 2011-2012): at the beginning of the synchronised operation period, net transfer capacities will be kept low (up to total 300 MW from Turkey to Greece/Bulgaria and 400 MW from Greece/Bulgaria to Turkey) in order to further test the interconnected system against possible inter-area oscillations and secondary control issues [17].

Then, in a short term the amount of interconnected power systems along the MedRing is going to be reduced to three.

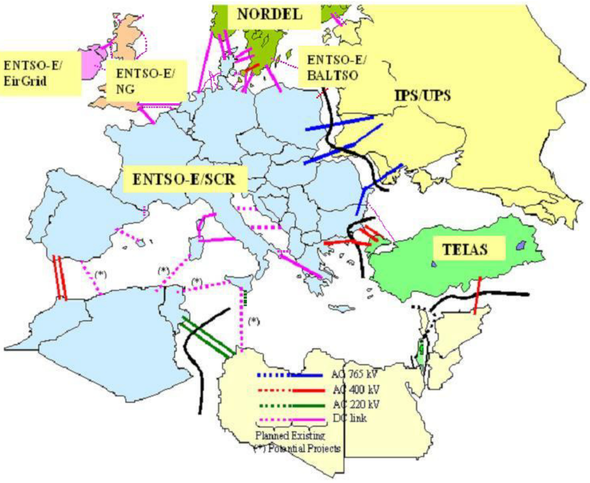

Figure 5: The European and Mediterranean synchronous areas (adapted from [29])

However, there are still some technical barriers ahead of the MedRing completion. Closure of the MedRing in HVAC mode, in accordance with the original plans, remains a very complicated target, especially upon the failure of latest attempt (Apr. 2010) to synchronise Tunisia (and the European continental network) with Libya, due to dynamics and stability issues [17]. On the other hand, being weak the interconnected grid, the adoption of high transmission reliability margins is required, therefore lowering net transfer capacities across the borders, which may at best reach 400 MW at 400/500 kV. For these reasons, if further synchronisation tests fail, the option of closing the MedRing

---

[17] At present Lebanese power system is still operated in an isolated way with the exception of some loads supplied in "islanded" mode from Syria through two existing lines [29].

by full HVDC lines or back-to-back HVDC systems across selected cut-sets/borders may be the most realistic: in fact, this would allow for higher net transfer capacities and for lower complexity in operating the interconnected systems. Moreover, the "decoupling", allowed by the HVDC solutions, can ensure a greater "independence" of each investment, reducing uncertainties. In this way, upon Turkish grid synchronisation with continental Europe's network, the two sections of the MedRing, that are still not synchronously interconnected, namely Tunisia-Libya and Turkey-Syria[18] borders, may be directly interlinked via HVDC (full or back-to-back) schemes. Further investigations on these options, as well as on the Israel-Palestinian Territories area coupling, are currently ongoing [28][29].

Yet, even in the case of MedRing closure via HVDC, the resulting transfer capacities in a mid-term horizon would not allow the export of solar (and wind) electricity on a larger scale. For this it is necessary to interconnect the two shores across the Mediterranean Sea by additional HVDC links.

The first cross-Mediterranean HVDC interconnection is the planned 2x500 MW link between Tunisia and Italy, to be operational by 2017-2020, upon reinforcement of the internal grid in Sicily. Further potential HVDC interconnections between southern Europe and northern Africa have been investigated in the recent years, concerning specifically the ties Algeria-Spain (2x1000 MW), Algeria-Italy (500-1000 MW), Libya-Italy (500-1000 MW) [18][29]. Some of these links may be put in operation by 2025-2030. One of the key technical barriers for interconnecting the two shores of the Mediterranean Sea is related to the difficulty in laying undersea cables below a certain sea depth. These technology constraints are mostly related to the risk of mechanical stress when laying down the cable from the special purpose ship. In case of high rating cables and a high depth, the weight of the cable can be reduced by using aluminium instead of copper for very depth sections. This solution has been adopted for the first time in the world for the newest Sardinia-Italian Peninsula (SAPEI) link, laid at a maximum sea depth of 1640 meters (world record). For high rate HVDC cables (1000 MW and above), the current technology allows a maximum depth of 1500-2000 meters. Higher depths might be reached, provided a reduction of the cable rating is acceptable. This leads to smaller cross-sections, less weight and, therefore, less mechanical stress [29].

Considering the morphology of the Mediterranean Sea in Figure 6, in which red areas highlight sea depth below 2000 meters and yellow areas signal sea depth in the range 1500-2000 meters, technical limitations may then significantly hinder the routing of new high power cross-Mediterranean corridors. With technology progress expected, this barrier could be overcome over the years, but possibly not before a mid-term horizon.

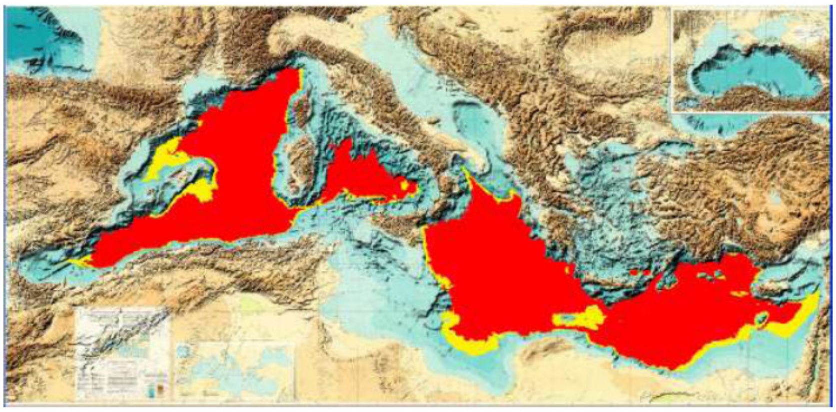

Figure 6: Morphology of the Mediterranean seabed (source: [29])

To foster the interconnections between the two shores of the Mediterranean Sea there exist some ambitious plans, like DESERTEC Industrial Initiative (DII) – EUMENA [30] and Medgrid (former Transgreen) [31], that at different levels, time horizons and scenarios foresee a large import of RES energy from the southern Mediterranean shore to Southern and Central Europe. This could bring different benefits like e.g.: enhanced diversification for EU electricity supply, hence increased security of supply; stronger regional integration of North-African countries in the EU energy market with an

---

[18] At the border Turkey-Syria, the currently practiced operational approach is "islanded mode" for local power exchanges only [29].

increased amount of commercial exchanges; broadened environmental sustainability due to larger exploitation of RES in the interconnected power system; expanded optimization of electricity generation in a larger and more integrated power system; improved technical performance of North-African power systems.

However, there are still several barriers and complex issues – at technical, regulatory, financing, market, socio-environmental and political level – that will not allow the implementation of such projects before 2030. In fact, at technical level, in addition to the limitations above described, a crucial problem is related to the preliminary need for extensive reinforcement of the internal grids of southern European countries prior to any large power transport therein from North Africa. Also, technological constraints for bulk power transport (e.g. 3-5 GW) are to be taken into due account. At regulatory, financing and market level, some of the existing gaps in the field refer to: lack of a sound financing framework and business model; necessity of incentive schemes to RES generation in North Africa, at least in the first stage; lack of shared and harmonized rules on network access, capacity allocation, congestion management and inter-TSO compensation; need for allocation and remuneration of the backup reserve/storage capacity to cope with imported RES volatility.

At socio-environmental and political level, one can refer particularly to the effects on local environment by bulk power interconnectors (e.g. in terms of visual impact, footprint and noise of HVDC converter stations and crossed sea impact of HVDC cables) and to their public acceptance as well as to the political instabilities in North African countries [29][32].

Central Eastern and South Eastern Europe

In Central and Eastern Europe the connection of new generation is a major challenge in a mid and long term horizon. Several network reinforcements and upgrades are then urgently needed, especially in Poland and Czech Republic and at the interfaces with Eastern and North-Eastern Germany, as well as within and between the grids of Slovakia, Austria and Hungary. At the same time, considering that more and more generation capacity in Germany is rather concentrated in the Northern and North-Eastern country regions, while load increases mostly in Southern Germany, where generally used balancing (e.g. pump storage) devices are also located [18]. Therefore, in presence of this power flow pattern change in Germany (which may be further significantly impacted by the upcoming nuclear phase-out), huge North-South transit capacities are needed, taking fully into account the grid development in and around the North Seas. As seen, this may make the use of HVDC for bulk power transport on the North-South axis an important option as embedded HVDC backbone (highway) and a significant step towards the realisation of a potential pan-European SuperGrid. This could be also further exploited upon completion of Germany-Austria-Italy interconnections to deliver RES energy from the North Seas to Southern Europe. A crucial link in this sense will be the one (foreseen via GIL) through the Brenner tunnel [18].

In South Eastern Europe, the transmission grid is rather less meshed respect to the rest of the continental grid. Also, a large potential for further hydro generation is present in the whole Balkan region. In a mid and long term, there is then a need for additional generation connection and interconnection capacities within and between the South East European countries and for increasing power flows also with Central Europe. Furthermore, the ongoing extension of the European synchronous continental zone from Greece and Bulgaria to Turkey will create additional needs for reinforcement of the grids in these countries. Other areas to be crucially expanded in a short, mid and long term will concern the East-West axis between the Adriatic Sea and the Black Sea countries through overhead and submarine interconnections (like the planned HVDC links Italy-Croatia, Italy-Montenegro, Italy-Albania, Romania-Turkey and the potential Italy-Greece doubling, see also Figure 5) as well as the corridors at the borders of Italy with Slovenia and Austria [18].

Regarding the further interconnections involving non-EU countries at the eastern borders of the European synchronous continental area, the most ambitious plan concerns the potential synchronous coupling of the European continental zone (former UCTE) with the Russian/CIS[19] IPS/UPS system. The main outcomes of the most recent study in the field [33] highlight that, even if a synchronous coupling appears viable, it must be considered only as a long term option: dynamic effects appear as the most limiting criteria for system extensions compared to steady-state load flow limitations. In

---

[19] CIS: Commonwealth of Independent States

general, the main criticalities refer to the overall complexity of a synchronous coupling first in the context of system security and overall reliability, but also from the point of view of operability of the underlying electricity markets and the legal and regulatory frameworks. For these reasons, non-synchronous system coupling possibilities by HVDC (in full or back-to-back links) are more and more evaluated by the involved TSOs [18][33]. The use of further innovative technologies (like FACTS and WAMS) is also being investigated towards a smart interconnection of the two systems [34].

At the borders of Russian system with Scandinavian countries, electricity trade may further increase over the years: this refers especially to the Finland-Russia interface, where power flows may be bidirectional via the HVDC back-to-back station in Vyborg (Russia), and also to the Norway-Russia border, where a supply from Russia is possible through separate islanding of local generators [26][32].

At the interface between Poland and Belarus, a new link may be realised (by 2017 [36]) via a 400 kV HVAC OHL (partially using the route of the existing, out-of-operation 220 kV OHL between the countries) equipped with a 600-1000 MW HVDC back-to-back station in Belarus.

In Ukraine, the so-called Burshtyn Power Plant Island, situated in the western part of the country, has been operated in parallel with the European synchronous continental system (former UCTE) since July 2002. The Burshtyn Island, which has direct interconnections with the grids of Slovakia, Hungary and Romania, is separated from the main grid of Ukraine by physical disconnections at three substations. One of the latter, Zakhidnoukrainska, is an end of a 750 kV EHVAC OHL – the only one of this type currently in operation in the ENTSO-E system – with the Hungarian grid. This 750 kV interconnection could also be one of the backbones of the potential pan-European SuperGrid. The other end of this 750 kV link is the Hungarian substation of Albertirsa, which due to ageing of equipment must be rebuilt by 2012-2013, but possibly in some other location, like in the Eastern Hungary substation of Debrecen, because of improved cost-benefit outcomes and increased operational security [18].

For other two existing 750 kV EHVAC OHLs - between Poland and Ukraine and between Romania and Ukraine (see also Figure 5) -, that are currently out-of-operation, the modernisation and resumption of equipment towards lines recommissioning have been planned by 2020 (for the former [36]) or put under study (for the latter). Both these infrastructures will need 1200 MW HVDC back-to-back stations, respectively in Poland (Rzeszów substation) and in Romania (Isaccea substation). The revitalisation of these two 750 kV EHVAC interconnections may be also seen towards the potential future synchronisation of Ukraine's full grid with the European continental zone.

Also the network of Moldova may be potentially fully synchronised with the European continental system in the future. Moldovan system is currently interconnected with Romanian grid via passive islanding and via 400 kV HVAC OHL serving for dedicated supply to Romania from some generating units of the Moldavskaya TPP plant, separated for export purposes from the Moldovan grid [26].

Ad hoc studies for assessing the possibility of synchronous coupling of both full grids of Ukraine and Moldova with the European continental network have been launched at ENTSO-E level [18].

CONCLUSIONS

The present paper, after introducing current European background, key HVDC features and main applications for bulk power transport outside Europe, focuses on ongoing developments and challenges towards the realisation of a potential pan-European HVAC/HVDC SuperGrid in a long term horizon. The main current and future evolutions at pan-European level, which can contribute to this SuperGrid realisation process, can be schematically recapped hereafter [3][37]:

- Strengthening interconnections (via HVDC submarine links or HVAC equipped with B2B) between Continental Europe, Scandinavian, British and Baltic countries (ongoing)
- Turkey - Continental Europe synchronisation (2011-2012)
- Embedding more HVDC links into the HVAC synchronous systems (ongoing)
- Development of offshore grids: North Sea, Baltic Sea, Irish Sea (from 2020)
- First North African - Continental Europe HVDC interconnection: Italy-Tunisia (by 2020)
- Development of overlay HVDC network in Continental Europe (Germany) (from 2020)
- Potential Moldova - Continental Europe synchronisation (after 2020)
- Strengthening interconnections (via HVAC equipped with B2B) between Continental Europe and Ukraine/Belarus (2020-2025)
- Potential Baltic - Continental Europe synchronisation (2020-2025)
- Potential MedRing closing (via HVDC) (2025-2030)

- Further North African - Continental Europe HVDC interconnections (from 2025-2030)

BIBLIOGRAPHY

[1] European Commission, “Energy infrastructure priorities for 2020 and beyond - A Blueprint for an integrated European energy network”, COM(2010) 677 final, Nov. 2010 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SPLIT_COM:2010:0677(01):FIN:EN:PDF

[2] Strategic Energy Technology Plan Information System (SETIS), Smart Electricity Grids, 2011 http://setis.ec.europa.eu/newsroom-items-folder/smart-electricity-grids-technology-information-sheet/at_download/Document

[3] European FP7 REALISEGRID project http://realisegrid.rse-web.it

[4] S. Rüberg, H. Ferreira, A. L’Abbate, U. Häger, G. Fulli, Y. Li, J. Schwippe, “Improving network controllability by Flexible Alternating Current Transmission Systems (FACTS) and by High Voltage Direct Current (HVDC) transmission systems”, REALISEGRID Deliverable D1.2.1, Mar. 2010 http://realisegrid.rse-web.it

[5] S. Rüberg, A. Purvins, “Comparison of AC and DC technologies for long-distance interconnections”, REALISEGRID Deliverable D1.3.3, Mar. 2010 http://realisegrid.rse-web.it

[6] J. Arrillaga, Y.H. Liu, N.R. Watson, “Flexible Power Transmission. The HVDC Options”, J. Wiley and Sons Ltd., 2007.

[7] CIGRE WG 14.20, “Economic Assessment of HVDC Links”, 2001.

[8] A. L’Abbate, G. Fulli, “Sustainability analysis of VSC-HVDC in the liberalised European power system: a practical case”, Proc. of 2009 IEEE PowerTech Conference, Bucharest (Romania), Jun. 28-Jul. 2, 2009.

[9] A. L’Abbate, G. Migliavacca, U. Häger, C. Rehtanz, S. Rüberg, H. Ferreira, G. Fulli, A. Purvins, “The Role of FACTS and HVDC in the future Pan-European Transmission System Development”, Proc. of the 9th IET Conference on AC and DC Power Transmission, London (UK), Oct. 20-21, 2010.

[10] Y. Xiao, Z. Wu, C. Hong, “Overview of HVDC Systems Operation in China Southern Power Grid”, CIGRE Session, Paris (France), Aug. 24-29, 2008.

[11] I. Vancers, D.J. Christofersen, A. Leirbukt, M.G. Bennett, “A Survey of the Reliability of HVDC Systems Throughout the World During 1999-2000”, CIGRE Session, Paris (France), Aug. 25-30, 2002.

[12] I. Vancers, D.J. Christofersen, A. Leirbukt, M.G. Bennett, “A Survey of the Reliability of HVDC Systems Throughout the World During 2001-2002”, CIGRE Session, Paris (France), Aug. 29-Sep. 3, 2004.

[13] I. Vancers, D.J. Christofersen, A. Leirbukt, M.G. Bennett, “A Survey of the Reliability of HVDC Systems Throughout the World During 2003-2004”, CIGRE Session, Paris (France), Aug. 27-Sep. 1, 2006.

[14] I. Vancers, D.J. Christofersen, A. Leirbukt, M.G. Bennett, “A Survey of the Reliability of HVDC Systems Throughout the World During 2005-2006”, CIGRE Session, Paris (France), Aug. 24-29, 2008.

[15] M.G. Bennett, N.S. Dhaliwal, A. Leirbukt, “A Survey of the Reliability of HVDC Systems Throughout the World During 2007-2008”, CIGRE Session, Paris (France), Aug. 22-27, 2010.

[16] European Commission, Joint Research Centre, Smart Electricity Systems http://ses.jrc.ec.europa.eu/

[17] ENTSO-E http://www.entsoe.eu

[18] ENTSO-E, “Ten-Year Network Development Plan (TYNDP) 2010-2020”, Jun. 2010 https://www.entsoe.eu/index.php?id=232

[19] A. Vaféas, S. Galant, T. Pagano, “Final WP1 report on cost/benefit analysis of innovative technologies and grid technologies roadmap report validated by the external partners”, REALISEGRID Deliverable D1.4.2, May 2011 http://realisegrid.rse-web.it

[20] ENTSO-E, “Study Roadmap towards Modular Development Plan on pan-European Electricity Highways System (MoDPEHS)”, document for consultation, May 2011 http://www.entsoe.eu

[21] European IEE OffshoreGrid project http://www.offshoregrid.eu

[22] ENTSO-E, “Offshore Grid Development in the North Seas”, Feb. 2011 http://www.entsoe.eu

[23] European FP7 TWENTIES project http://www.twenties-project.eu

[24] D. Jovcic, B.T. Ooi, “Developing DC Transmission Networks using DC Transformers”, IEEE Transactions on Power Delivery, Vol. 25, Oct. 2010, pp. 2535–2543.

[25] European Commission, BEMIP http://ec.europa.eu/energy/infrastructure/bemip_en.htm

[26] Inter-RAO http://www.interrao.ru/en

[27] NORDEL (now ENTSO-E), “Market based analysis of interconnections between Nordic, Baltic and Poland areas in 2025”, Feb. 2009 https://www.entsoe.eu/fileadmin/user_upload/_library/publications/nordic/planning/090210_entsoe_nordic_MultiregionalPlanningProjectReport.pdf

[28] European Commission, Mediterranean energy plan http://ec.europa.eu/energy/international/euromed_en.htm

[29] MED-EMIP (Euro-Mediterranean Energy Market Integration Project), “MEDRING Update Study: Mediterranean electricity interconnections”, Apr. 2010 http://www.medemip.eu

[30] DESERTEC Industrial Initiative (DII) – EUMENA http://www.dii-eumena.com

[31] Medgrid project http://www.medgrid-psm.com

[32] European FP7 SECURE project http://www.secure-ec.eu

[33] UCTE - IPS/UPS, “Feasibility Study: Synchronous Interconnection of the Power Systems of IPS/UPS with UCTE”, Nov. 2008 http://www.ucte-ipsups.org/

[34] European FP7 ICOEUR project http://www.icoeur.eu

[35] A. L’Abbate, I. Losa, G. Migliavacca, A.R. Ciupuliga, M. Gibescu, H. Auer, K. Zach, “Possible criteria to assess technical-economic and strategic benefits of specific transmission projects”, REALISEGRID Deliverable D3.3.1, Apr. 2010 http://realisegrid.rse-web.it

[36] PSE-Operator http://www.pse-operator.pl

[37] European FP7 SUSPLAN project http://www.susplan.eu

Acknowledgment: The research leading to these results has received partial funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 219123 (REALISEGRID project)