Energy

Briefing: The North Sea grid
Adeuyi and Wu

ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/ener.14.00027
Paper 1400027
Received 14/09/2014 Accepted 09/03/2015
Keywords: electrical engineering & distribution/offshore engineering/renewable energy

ice
Institution of Civil Engineers
publishing

Briefing: The North Sea grid

[1] **Oluwole Daniel Adeuyi** BSc, MSc, MIET
Research Assistant, Institute of Energy, Cardiff University, Cardiff School of Engineering, Cardiff, UK

[2] **Jianzhong Wu** BSc, MSc, PhD, MIEEE, MIET
Reader, Institute of Energy, Cardiff University, Cardiff School of Engineering, Cardiff, UK

It is estimated that ~33 GW of offshore wind capacity will be installed in the North Sea by 2020, and this is expected to increase to 83 GW by 2030. The North Sea grid is a concept that is intended to transfer the electricity generated from offshore wind farms installed in the North Sea to land, interconnect the grids of adjacent countries and facilitate the creation of a European internal electricity market. This briefing note explains the North Sea grid concept and the basic principles of high-voltage direct current submarine power transmission.

1. Introduction

The North Sea grid is a concept that is intended to transfer power generated from offshore wind farms installed in the North Sea to land, interconnect the grids of adjacent countries and facilitate the creation of a European internal electricity market. Several proposals of the North Sea grid concept exist in the literature. The Airtricity Foundation Project (Airtricity, 2006) proposed 10 GW offshore wind farms to be connected to the grids of the UK, Germany and the Netherlands. Greenpeace (2008) reported that about 65 GW of offshore wind capacity could be connected to the grids of seven countries around the North Sea. The Friends of the Supergrid (FOSG, 2011) proposed to develop the North Sea grid in phases. The first phase is to integrate 23 GW of offshore wind capacity from the UK, German and Belgian offshore wind farm clusters into the grids of four countries (the UK, Germany, Belgium and Norway). The European Network of Transmission System Operators for Electricity (ENTSO-E, 2011) estimated that 33 GW of offshore wind capacity will be installed in the North Sea by 2020 and 83 GW by 2030. In 2010, ten countries (Sweden, Denmark, Germany, the Netherlands, Luxembourg, France, the UK, Ireland, Norway and Belgium) signed a memorandum of understanding to develop an integrated North Sea grid and formed the North Sea Countries Offshore Grid Initiative (NSCOGI, 2011).

The proposed North Sea grid would use both high-voltage direct current (HVDC) and high-voltage alternating current (HVAC) for submarine electrical power transmission. HVAC transmission is mature and well understood. HVDC has better control capabilities, reduced asset footprint and lower power losses. In addition, HVDC can interconnect power systems operating at different frequencies and phase angles. At transmission distances beyond 70–80 km and at a voltage of 150kV and above, HVAC is not practical due to the capacitance and hence charging current of the submarine cable. ENTSO-E (2011) estimated that the ratio of HVDC to HVAC submarine power cable capacities to be installed in the North Sea will be ~4:1 by 2030. This briefing note explains the North Sea grid concept and the basic principles of HVDC submarine power transmission.

2. Submarine electrical power systems

The electrical system of an offshore wind farm consists of a medium-voltage electrical collection network and a high-voltage electrical transmission connection. Figure 1 shows the simplified electrical system of an offshore wind farm in the North Sea. The collection grid uses transformers in each wind turbine to step up the generation voltage of the wind turbines from 690 V to a medium voltage of 25–40 kV. A network of medium-voltage alternating current (AC) cables connects the offshore wind turbines to an offshore AC substation. The transmission connection uses the offshore AC substation to transform the medium voltage to a high voltage of 130–150 kV for connection to an offshore converter station.

Remote offshore wind farms use offshore converter stations to transform the AC generated from the offshore wind turbines into direct current (DC). These offshore converter stations are mounted on offshore converter platforms. HVDC submarine power cables connect the offshore converter platforms to shore as shown in Figure 1. At the other end of the submarine

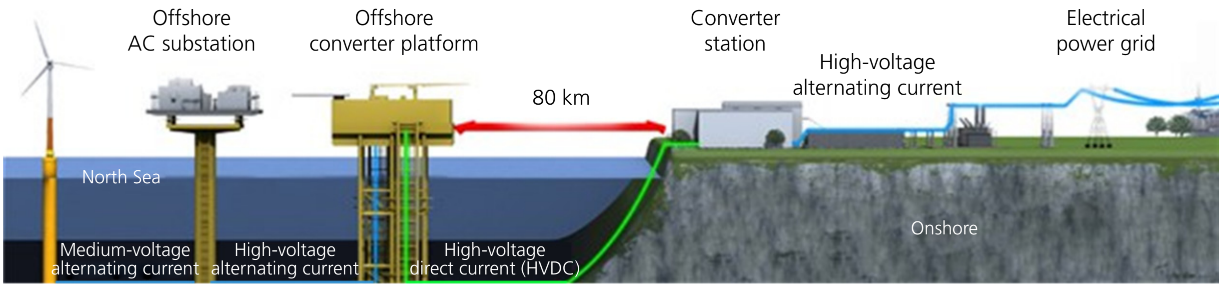

Figure 1. Simplified electrical system of an offshore wind farm. Copyright Alstom

cables, onshore converter stations receive the power from the wind farms and convert it back to AC, which is fed into the terrestrial power grid. The three key components of the HVDC networks of the proposed North Sea grid are offshore converter platforms, submarine power cables and onshore converter stations. The HVDC submarine power cables can also interconnect the grids of two or more countries, thereby creating an offshore grid.

2.1 Offshore converter platforms

The two main components of an offshore converter platform are the topside and the foundation support structure. Topsides house the offshore HVDC converter stations. Foundation support structures host the topsides. The three possible foundation support structures are fixed, mobile jack-up and gravity base. The fixed platforms use jacket support structures that are attached to the seabed through piles. The topsides and jackets are installed by lifting from a barge using a heavy-lift crane vessel. The topside of a 1000 MW HVDC converter platform could weigh up to 10 000 t and this will require a large crane vessel. This has implications for both costs and availability and multiple offshore lifts (ABB, 2012a).

A mobile jack-up platform has a self-installing topside that is mounted on a substructure. These topsides house offshore converter platforms, which have an embedded jack-up system. The substructure is formed by steel piles that are installed around 50 m deep into the seabed. The floating topside is towed into position directly above the substructure and raised up to about 20 m above sea level by the embedded jack-up system. This approach does not require a large crane vessel. This concept was applied to the 864 MW Sylwin1 converter platform with dimensions of $83 \times 56 \times 40$ m (length × width × height) and a total weight of 25 000 t (Siemens, 2014).

The gravity-based platform consists of a topside welded to a gravity-based support (GBS) structure. These GBS platforms are constructed onshore, towed into position and secured on the seabed by their own weight and ballasting. This approach eliminates the need for heavy-lift vessel or offshore jack-up operations. The 900 MW DolWin2 project under construction will use the self-installing gravity-based structure platform for efficient production and ease of installation (ABB, 2012a).

2.2 Submarine power cables

According to the ENTSO-E (2014) 10-year network development plan, about 20 000 km of HVDC subsea power cables are required by 2030, of which 14 000 km (i.e. about 70%) are to be installed in the North Sea. Cable manufacturers would need to expand their production capabilities and more cable-laying vessels would be required to meet the predicted demand.

The two HVDC submarine power cable technologies available on commercial terms are mass-impregnated (MI) paper cables and extruded cross-linked polyethylene (XLPE) plastic cables. The central conductor of these cables is made either of copper or aluminium. The insulation of MI paper cables consists of clean paper impregnated with a high-viscosity compound based on mineral oil. The next generation of MI paper cables would use paper polypropylene laminate as insulation to achieve ratings of 650 kV and 1500 MW per cable. A single-core MI paper cable could have a conductor size of up to 2500 mm^2 and weigh about 37 kg/m (ABB, 2014). HVDC submarine cables have a sheathed and armoured layer for protection against harsh conditions associated with offshore installation and service (ABB, 2014). Table 1 is a summary of the latest HVDC submarine power cables (FOSG, 2011; National Grid, 2012).

2.3 Onshore converter stations

There are two main HVDC converter technologies: line-commutated converter (LCC) and self-commutated voltage source converter (VSC). Table 2 is a summary of the status of HVDC converters (Cao and Cai, 2013; National Grid, 2012).

Cable technology	Maximum ratings per cable: Installed (until 2014) Capacity: GW	Voltage: kV	Under construction Capacity: GW	Voltage: kV	Achievable (up to 2020) Capacity: GW	Voltage: kV
XLPE	0·25	200	0·5	320	1	500
MI	0·6	500	0·8	500	1·5	600–650 (PPLP technology)

XLPE, extruded cross-linked polyethylene; MI, mass impregnated; PPLP, paper polypropylene laminate

Table 1. Status of HVDC Cables

Converter technology	Maximum ratings per converter: Installed (until 2014) Capacity: GW	Voltage: kV	Under construction Capacity: GW	Voltage: kV	Achievable (up to 2020) Capacity: GW	Voltage: kV
LCC	7·2	±800	8	±800	10	±1100
VSC	0·5	±200	1	±320	2	±500
			0·7	500[a]		

[a]Converters have one pole
LCC, line-commutated converter; VSC, self-commutated voltage source converter

Table 2. Status of HVDC converters

LCC-HVDC is a mature technology and suitable for long-distance bulk power transfers. VSC-HVDC is a more recent development and has independent control of active and reactive powers, improved black start capability and occupies less space than LCC-HVDC. Therefore, VSC-HVDC is the key technology for offshore wind power transmission and the North Sea grid. MI paper cables are suitable for both LCC and VSC applications. Extruded XLPE insulation cables are suitable for VSC applications and are available at voltages of up to 500 kV.

3. National strategies

Within the proposed 83 GW of offshore wind capacity to be installed in the North Sea by 2030, 38·5 GW will be off the coast of the UK and 24 GW off the coast of Germany (ENTSO-E, 2011). In the UK, most offshore transmission circuits will be connected to the shore using VSC-HVDC platforms each rated at 1 GW and ±320 kV (National Grid, 2012). In Germany, offshore wind farms have been grouped into 13 clusters, and most of the offshore VSC-HVDC platforms are each rated at up to 900 MW and ±320 kV (BSH, 2012). In Belgium, the total power from offshore wind farms will be aggregated through two offshore HVAC platforms with a combined capacity of 2·3 GW. The two platforms will be inter-tied and connected to an onshore substation using 220 kV AC submarine cables. This design includes future interconnectors with France and the UK through an international HVDC platform rated at up to 3 GW and above ±500 kV (Elia, 2013). From Norway, new HVDC interconnectors are planned to the EU, rated at up to 1·4 GW and ±500 kV (STATNETT, 2011).

4. Development of interconnectors in the North Sea

Interconnectors use submarine power cables to connect the electricity transmission systems of adjacent countries. Interconnection could allow electricity to flow from one country to another according to the market prices on either side of the interconnector. At present, four countries (Great Britain, the Netherlands, Denmark and Norway) have 3·4 GW of interconnection capacity through six HVDC interconnectors in the North Sea. Figure 2 shows the existing and proposed HVDC interconnectors to be installed in the North Sea by 2020. Table 3 is a summary of the existing and proposed subsea interconnection capacities to be installed in the North Sea by 2020.

It is estimated that ten HVDC subsea interconnectors – having a total capacity of about 9·3 GW and a total route length of about 3800 km – will be installed in the North Sea by 2020.

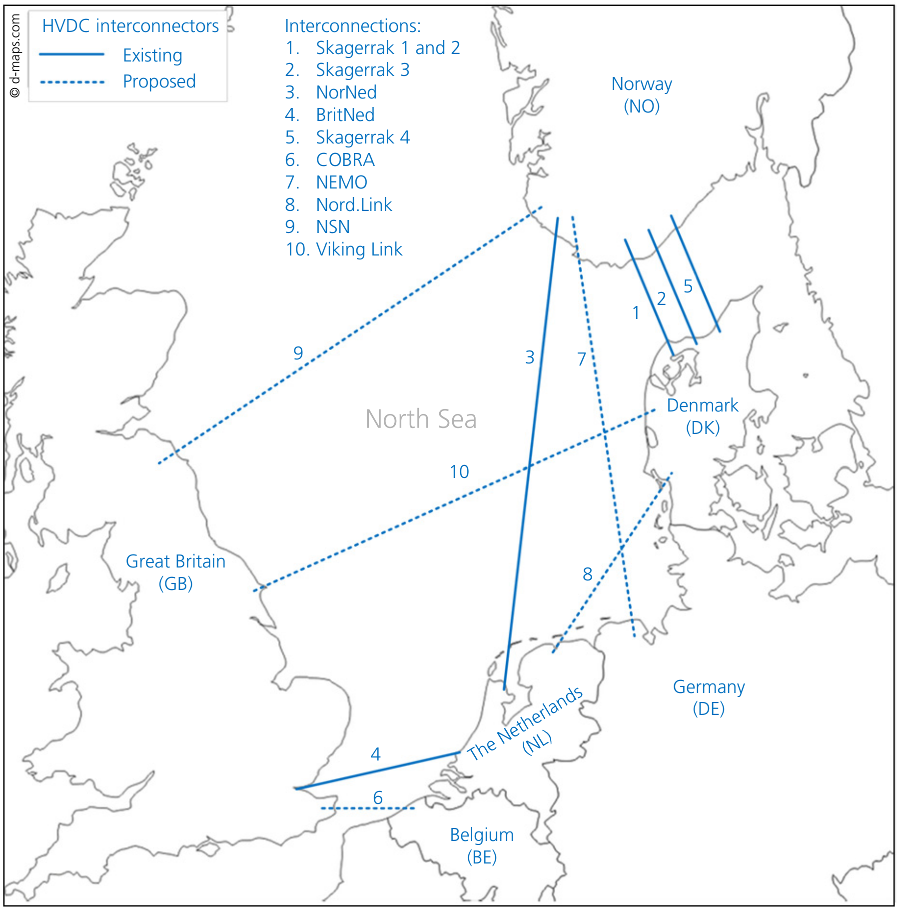

Figure 2. Existing and proposed HVDC interconnectors in the North Sea by 2020. Copyright d-maps.com

	Country	Project name	Completion date	Capacity: MW	Route length: km	Voltage: kV	Converter technology
1	DK–NO	Skagerrak 1 and 2	1977	500	127	±250	LCC
2	DK–NO	Skagerrak 3	1993	500	127	350	LCC
3	NL–NO	NorNed	2009	700	580	±450	LCC
4	GB–NL	BritNed	2011	1000	250	±450	LCC
5	DK–NO	Skagerrak 4	2014	700	140	500	VSC
6	BE–GB	NEMO	2018	1000	135	±250	LCC
7	DE–NO	Nord.Link	2018	1400	600	±500	LCC
8	DK–NL	COBRA	2019	700	350	±320	VSC
9	GB–NO	NSN	2020	1400	800	±500	LCC
10	DK–GB	Viking link	2020	1400	700	—	—
Total				9300	3809		

BE, Belgium; DE, Germany; DK, Denmark; GB, Great Britain; NL, the Netherlands; NO, Norway; LCC, line-commutated converter; VSC, self-commutated voltage source converter

Table 3. Subsea interconnection capacities in the North Sea by 2020

Two of these interconnectors use the VSC technology. In December 2014, the new VSC-based Skagerrak 4 project, which connects Denmark and Norway, was commissioned to work in parallel with the existing LCC-based Skagerrak 3. This hybrid of a VSC and an LCC scheme is the first to operate in such a bipole configuration. The proposed COBRA interconnector would use a single subsea cable to integrate offshore windfarms and interconnect the grids of Denmark and the Netherlands by 2019. This will exemplify the first steps in the development of a multi-terminal HVDC system in the North Sea.

5. Visions of the future North Sea grid

Existing HVDC subsea cables of the North Sea grid are point-to-point circuits, and each circuit provides a single service either for interconnecting transmission grids or connecting offshore generators to onshore grids (Lévêque *et al.*, 2012). Although the topology of the future North Sea grid has not been agreed, ENTSO-E (2011) has proposed two possible topologies: (*a*) local coordination and (*b*) fully integrated. The local coordination topology assumes a continuation of existing offshore grid development regimes. This will result in a multiplication of point-to-point circuits in the North Sea. The fully integrated topology is intended to interconnect several point-to-point circuits and offshore wind power generation units. This will create a multi-terminal HVDC system, in which any unused transmission capacity when wind farms are operating below their peak generation can be used for balancing and energy trading between the grids of different countries (Lundberg *et al.*, 2012). However, reliable operation of such multi-terminal HVDC schemes will require high-power DC circuit breakers and DC flow control devices, which are still being developed. Manufacturers of DC circuit breakers have announced the results of prototype tests in which DC exceeding 3 kA was interrupted in <3 ms (ABB, 2012b; Alstom, 2013). The next step is to deploy such DC breakers into real HVDC networks.

6. Conclusions

The North Sea grid concept is intended to transfer the power generated from offshore wind farms installed in the North Sea to land and interconnect the grids of adjacent countries. HVDC will be the key technology for submarine electrical power transmission in the proposed North Sea grid. LCC-HVDC is a mature technology and suitable for interconnection of transmission girds of different countries. VSC-HVDC is suitable for offshore wind power transmission. The major components of the HVDC networks of the proposed North Sea grid are offshore converter platforms, submarine power cables and onshore converter stations.

Strategic development of the North Sea grid sets a number of challenges involving technical, economic, financial, environmental and socio-political aspects (FOSG, 2014). To address some of these challenges, ENTSO-E, NSCOGI and the Agency for the Cooperation of Energy Regulators are to design regulatory frameworks for coordinated development and management of the North Sea grid (NSCOGI, 2012). The proposed North Sea grid could help to lower electricity supply prices, reduce the cost of delivering security of supply and support the decarbonisation of electricity supplies in the EU.

Acknowledgements

The authors acknowledge the financial support of this work by the Research Councils UK, through the HubNet consortium, http://www.hubnet.org.uk (grant number: EP/I013636/1) and the Top & Tail Transformation programme, http://www.topandtail.org.uk (grant number: EP/I031707/1).

REFERENCES

ABB (Asea Brown Boveri Ltd) (2012a) *FFWD, Focus on Offshore Renewables Special Issue*. ABB, Staffordshire, UK. See http://new.abb.com/docs/librariesprovider53/magazines-downloads/ffwd-2-12.pdf?sfvrsn=4 (accessed 24/08/2014).

ABB (2012b) *The High Voltage DC Breaker – The Power Grid Revolution*. ABB, Zurich, Switzerland. See http://www04.abb.com/global/seitp/seitp202.nsf/c71c66c1f02e6575c125711f004660e6/afefc067cd5a69c3c1257aae00543c03/$FILE/HV+Hybrid+DC+Breaker.pdf (accessed 22/04/2013).

ABB (2014) *HVDC Mass Impregnated Cables*. ABB, Zurich, Switzerland. See http://new.abb.com/systems/high-voltage-cables/cables/hvdc-mi-cables (accessed 03/09/2014).

Airtricity (2006) *European Offshore Supergrid Proposal: Vision and Executive Summary*. Airtricity, London, UK.

Alstom (2013) *Alstom Takes World Leadership in a Key Technology for the Future of Very High Voltage Direct Current Grids*. Alstom, Levallois-Perret, France. See http://www.alstom.com/press-centre/2013/2/alstom-takes-world-leadership-in-a-key-technology-for-the-future-of-very-high-voltage-direct-current-grids/ (accessed 22/04/2013).

BSH (Bundesamt für Seeschifffahrt und Hydrographie) (2012) *Draft Offshore Network Plan for German Exclusive Economic Zone of the North Sea*. BSH, Hamburg, Germany. See http://www.bsh.de/de/Meeresnutzung/Offshore-Netzplan/Dokumente/Entwurf_ONPN_final.pdf (accessed 09/02/2013).

Cao J and Cai JY (2013) HVDC in China. *Proceedings of the 2013 EPRI High Voltage Direct Current and Flexible Alternating Current Transmission Systems Conference, Palo Alto, CA, USA*. See http://dsius.com/cet/HVDCinChina_EPRI2013_HVDC.pdf (accessed 22/03/2014).

Elia (2013), *High Voltage Grid in the North Sea: A Vision for the Future*. Elia, Brussels, Belgium. See http://www.eliagroup.eu/~/media/files/elia/publications-2/brochures/hvgridnorthsea-vision.pdf (accessed 31/01/2013).

ENTSO-E (European Network of Transmission System Operators for Electricity) (2011) *Offshore Grid Development in the North Seas ENTSO-E Views.* ENTSO-E, Brussels, Belgium. See https://www.entsoe.eu/resources/publications/system-development/north-seas-grid-development/.

ENTSO-E (2014) *Regional Investment Plan 2014 North Sea Region*. ENTSO-E, Brussels, Belgium.

FOSG (Friends of the Supergrid) (2011) *Roadmap to the Supergrid Technologies.* FOSG, Brussels, Belgium. See http://mainstream-downloads.opendebate.co.uk/downloads/FOSG_WG2_Final-report.pdf (accessed 31/10/2012).

FOSG (2014) *Supergrid Preparatory Phase: Review of Existing Studies and Recommendations to Move Forwards.* FOSG, Brussels, Belgium. See http://www.friendsofthesupergrid.eu/wp-content/uploads/2014/03/REPORT-rev212.pdf (accessed 14/08/2014).

Greenpeace (2008) *A North Sea Electricity Grid Revolution*. Greenpeace, London, UK. See http://www.greenpeace.org/eu-unit/Global/eu-unit/reports-briefings/2009/5/-North-Sea-electricity-grid-(r)evolution.pdf (accessed 22/07/2013).

Lévêque F, Meeus L, Azevedo A, Saguan M and Glachant JM (2012) *Offshore Grids: Towards a Least Regret EU Policy. THINK Topic 5, Final Report*. THINK, Brussels, Belgium. See http://www.eui.eu/Projects/THINK/Documents/Thinktopic/THINKTopic5.pdf (accessed 05/06/2015).

Lundberg P, Callavik M, Bahrman M and Sandeberg P (2012) Platforms for change: high-voltage DC converters and cable technologies for offshore renewable integration and DC grid expansions. *IEEE Power and Energy Magazine* **10(6)**: 30–38.

National Grid (2012) *Electricity Ten Year Statement*. National Grid, London, UK. See http://www.nationalgrid.com/NR/rdonlyres/DF56DC3B-13D7-4B19-9DFB-6E1B971C43F6/57770/10761_NG_ElectricityTenYearStatement_LR.pdf.

NSCOGI (North Sea Countries Offshore Grid Initiative) (2011) *NSCOGI Report 2011*. NSCOGI, Brussels, Belgium. See http://ec.europa.eu/energy/infrastructure/tent_e/doc/off_shore_wind/2011_annual_report_annex2_en.pdf (accessed 16/10/2012).

NSCOGI (2012) *Final Report Working Group 1 – Grid Configuration*. NSCOGI, Brussels, Belgium. See http://www.benelux.int/NSCOGI/NSCOGI_WG1_OffshoreGridReport.pdf (accessed 21/03/2013).

Siemens (2014) *Siemens Installs Two Offhsore Platforms for TenneT in the North Sea in July.* Siemens, Erlangen, Germany. See http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2014/energy/power-transmission/ept201407058.htm (accessed 24/08/2014).

STATNETT (2011) *Grid Development Plan Summary.* STATNETT, Oslo, Norway. See http://www.statnett.no/Documents/Kraftsystemet/Nettutviklingsplaner/Griddevelopment plan summary 2011.pdf (accessed 04/02/2013).

WHAT DO YOU THINK?

To discuss this briefing, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions sent in by civil engineering professionals, academics and students. Papers should be 2000–5000 words long (briefing papers should be 1000–2000 words long), with adequate illustrations and references. You can submit your paper online via www.icevirtuallibrary.com/content/journals, where you will also find detailed author guidelines.