The National
HVDC Centre

Part of Scottish & Southern Electricity Networks

HVDC Technology Capability

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Abbreviations

Abbreviation	Meaning
A	Amperes
AC	Alternating current
EU	European Union
G	Giga (x10^9)
HVDC	High Voltage Direct Current
k	Kilo (x10^3)
LCC	Line Commutated Converter
m	meter
M	Mega (x10^6)
MI-PPL	Mass Impregnated Polypropylene Laminate
P	Real Power
PILC	Paper Insulated, Lead Covered
Q	Reactive Power
SQSS	Security and Quality of Supply Standard
V	Voltage / Volts
VA	Volt-Amperes (measure of apparent power)
VSC	Voltage Source Converter
W	Watts (measure of real power)
XLPE	Cross-linked polyethylene

1 Background

The National HVDC Centre ("the HVDC Centre") produced this report for the Eastern HVDC Link project team. The report is a high-level technology review with a view to informing project specification of the proposed HVDC link.

This was the first engagement for the HVDC Centre with this client which is expected to be the start the Centre's ongoing support of the project. Following this piece of work, the Centre has been asked to provide a proposal to provide an Integration Risk Management Strategy for the Eastern HVDC Link.

2 Introduction

The Eastern Link HVDC Project team had previously made certain assumptions on what technology would be available for delivery pre-2020, based on the technology and manufacturers available at that time. Now that the project delivery date has moved back, more technologies and other manufacturers of HVDC links may be available; which could be suitable for a project due for contract placement around 2021-23.

In order to determine the optimal solution for the East Coast Reinforcement, the three Transmission Owners (SPT, SHETL & NGET) aim to refresh the research carried out in 2013 through engagement with The National HVDC Centre to determine what will be feasible to deliver by the project contract placement date of around 2021-23.

As part of this research, The National HVDC Centre was asked to investigate three main questions:

1. Is it reasonable to assume that the technology will be available to commission an offshore HVDC VSC link with a rating of 2GW with the anticipated contract placement date of around 2021-23?
2. Is there potential for an offshore HVDC VSC link with a rating greater than 2GW? If so, what level of capacity may reasonably be obtained?
3. Are there limiting grid network characteristics, for example, available short circuit level that are required to be satisfied to enable a practicable HVDC VSC link of the ratings indicated in the preceding points?

This report answers these questions by: identifying what is being offered by suppliers; identifying relevant existing and contracted schemes; investigating grid limitations; and highlighting key developments in future technology.

This report is split into 7 sections:

- This section (Section 1) is the introduction;
- Section 2 details a review of supplier information;
- Section 3 lists relevant existing and contracted schemes;
- Section 4 discusses any grid limitation;
- Section 5 provides details of future technologies;
- Section 6 gives discussion of the conclusions of the work undertaken; and
- Section 7 details the references used.

3 Literature Review of Supplier Information

There are a small number of suppliers of VSC technology globally [1]. The two key aspects which limit the capability of the scheme are the valves and the cables. Currently the limiting factor for VSC schemes involving a subsea link is the availability of cables with sufficient voltage ratings.

From the review it can be seen that converters with ratings in excess of 500 kV are coming to the market resulting in the ratings of several gigawatts. The cable technology for these voltage ratings has undergone major development phase. However, perceived risk of first deployment and abundance of mature technology at ±320 kV from all major suppliers has meant that this voltage level has been the preferred option. The highest rating offered by non-European suppliers in the European market is still limited to ±320 kV and therefore a power output of 1 GW will be a safe assumption.

3.1 ABB

The VSC product offered by ABB is called HVDC Light. ABB is a market leader in VSC technology with over 20 years experience in the technology [2]. ABB sold its cables business to NKT in 2016 but still has access to the products through a long term partnership [3]. Their documentation states valves of ratings up to ±640 kV are available with ratings up to 3270 MVA for asymmetrical monopole topology [4]. The highest rating of subsea cable though appears to be 525 kV with a resultant rating of 2.6 GW [5].

3.2 GE Network Solutions

The VSC product offered by GE (previously Alstom) is called MaxSine. GE has been developing this technology for many years and has a track history of projects in the field [6]. There is no publically available information which gives specific voltage or power capabilities of their converters [7]. Based on their current projects, they have a capability of at least ±325 kV.

3.3 Mitsubishi

The VSC product offered by Mitsubishi is called HVDC Diamond. They are new to the market, having announced the product in 2016 with the creation of a test facility in Japan [8]. There is little information available about the ratings that they can offer and they are yet to win a commercial contract. It is understood that their ambition is to offer a VSC HVDC converter rated at ±320 kV. They do however have experience of HVDC through LCC schemes such as the Kii-Channel HVDC System [9].

3.4 Nexans (Cable Supplier Only)

The latest press release from Nexans about HVDC cable capability is from September 2016 [10]. At that time they state XLPE cables available to ratings of 320 kV with type testing complete for 525 kV. For PILC type cables there is an available rating of 600 kV, which they equate to a transmission capacity of 1900 MW in a bipole configuration.

More recently Nexans has confirmed that an order has been placed for two 320 kV cables with a combined rating of 900 MW for the connection to DolWin6 [11].

3.5 NKT (Cable Supplier Only)

NKT issued a paper this year detailing their latest developments in HVDC cables [12]. They state that they can now produce a 640 kV XLPE cable, which they equate to a limit of greater than 3 GW.

3.6 Prysmian (Cable Supplier Only)

Prysmian provided an update on their HVDC capability in April of 2017 [13]. It stated the capability to produce 600 kV rated XLPE cables, which they equate to 3.5 GW per bipole, and 700 kV rate MI-PPL type cables.

3.7 RXPE

The VSC product offered by RXPE is called Smart VSC-HVDC. They are new to the market but have already completed a number of projects within China. They have recently announced type testing of an 800 kV, 5 GW valve [14]. However, rigour of their claim to commercial deployment, especially to European standards remains unclear. They do not have any HVDC deployments in any Europe so far.

3.8 Siemens

The VSC product offered by Siemens is called HVDC Plus. They are heavily involved in ongoing HVDC projects and have a good track record in the technology. They do not have a readily available list of equipment ratings however they have recently commissioned a 2 x 1 GW scheme involving a cable system (although not subsea) [15].

3.9 Other Suppliers

There are a number of other suppliers globally for both valves and cables. However, these are also limited in number and generally serve home markets. As yet, they have not penetrated the European cable and converter markets at voltage above 320 kV [1].

4 Operational and Future Schemes

A list of both the currently operational schemes and likely future schemes follow in Table 1 and

Table 2 respectively [16]. As can be observed, a rating of 2 GW would be bigger than any existing subsea HVDC and one of the biggest future schemes currently being discussed. The biggest submarine transmission schemes under construction has a rating of 1400MW with ±525 kV.

Table 1: Existing VSC HVDC Schemes

Name	Year Commissioned	Power (MW)	DC Voltage (kV)	Transmission Length (km)	Converter Manufacturer
Hällsjön - Sweden	1997	3	±10	10	ABB
Gotland, Sweden	1999	50	±80	70	ABB
Direct Link / TerraNora, Aus.	2000	3x60	±80	59	ABB
Tjaereborg, Den.	2000	7.2	±9	4.3	ABB
Eagle Pass, USA	2000	36	±15.9	Back to Back	ABB
Cross Sound, USA	2002	330	±150	40	ABB
Murraylink, Australia	2002	220	±150	180	ABB
Troll A, Norway	2005	2x44	±60	70	ABB
Estlink, Finland	2006	350	±150	31 (underground) 74 (submarine)	ABB
Caprivi Link, Namibia	2010	300	±350	950	ABB
Trans Bay Cable, USA	2010	400	±200	85	Siemens
Valhall, Norway	2011	78	150	292	ABB
Nanhui	2011	18	±30	8.4 (underground)	C-EPRI
East-West Link, Ireland-UK	2013	500	±200	75 (underground) 186 (submarine)	ABB
Nan’ao Island	2013	200, 150, 50	±160	Multi-terminal	RXPE, XiDian, NR-Electric
Zhoushan, China	2014	400, 300, 3x100	±200	Multi-terminal, 129 subsea	C-EPRI/NR Electric
Mackinac, USA	2014	200	±71	Back to Back	ABB
Skagerrak 4, Norway-Denmark	2014	700	500	104 (underground) 140 (submarine) (in bipole with LCC)	ABB
BorWin1, Germany	2015	400	±150	75 (underground) 125 (submarine)	ABB
BorWin2, Germany	2015	800	±300	75 (underground) 125 (submarine)	Siemens
HelWin1, Germany	2015	576	±250	45 (underground) 85 (submarine)	Siemens
INELFE, France-Spain	2015	2x1000	±320	65	Siemens

Name	*Year Commissioned*	*Power (MW)*	*DC Voltage (kV)*	*Transmission Length (km)*	*Converter Manufacturer*
SylWin1, Germany	2015	864	±320	45 (underground) 160 (submarine)	Siemens
HelWin2, Germany	2015	690	±320	46 (underground) 85 (submarine)	Siemens
Dolwin1, Germany	2015	800	±320	90 (underground) 75 (submarine)	ABB
Xiamen, Fujian Province	2015	1000	±320	10.7 (Bipolar)	C-EPRI
Troll 3&4	2015	2x50	±60	70	ABB
Ål-link – Finland	2015	100	±80	158 (submarine)	ABB
Luxi, Yunnan Province China	2016	1000	±350	Back to Back	China Southern Grid, RXPE (Yunnan) XD Group/IEECAS
NordBalt, Sweden	2016/17	700	±300	450	ABB
DolWin2, Germany	2017	916	±320	45 (underground) 90 (submarine)	ABB

Table 2: Future VSC HVDC Schemes

Name	Year to be Commissioned	Power (MW)	DC Voltage (kV)	Transmission Length (km)	Converter Manufacturer
Maritime Link	2017	500	±200	187 OHL, 170 submarine, bipole	ABB
SW Link, Sweden (SydVästlänken)	2017/18	2x600	±300	190 underground cable, 60 OHL	GE
Yu'E	2017/18	1250x4	±420	Back to Back , 2 parallel pairs	RXPE
DolWin3, Germany	2018	900	±320	80 (underground) 80 (submarine)	GE
Caithness-Moray-Shetland	2018	1200	±320	160	ABB
Johan Sverdrup	2018	100	±80	200 (2 circuits)	ABB
Zhangbei phase 1	2018	3000, 1500x2	±500	Unknown	Unknown
Chongqing-Hubei HVDC	2018	2500	420	Back to Back	Unknown
Cobra Cable, Neth.-Denmark	2019	700	±320	325	Siemens
NEMO GB-Belgium	2019	1000	±400	140	Siemens
BorWin3	2019	900	±320	30 (underground) 130 (submarine)	Siemens
Italy-France	2019	2x600	±320	190	Unknown
Krigers-Flak Combined Solution	2019	410	±140	Back to Back	ABB
ElecLink, UK-France	2020	1000	±320	51	Siemens
IFA2, UK-France	2020	1000	Unclear	240	ABB
Western-Isles Scotland	2020	450	Unclear	80 subsea 76 underground	Unknown
Nordlink, Germany-Norway	2020	1400	±525	54 (underground), 516 (submarine)	ABB
Zhangbei phase 2	2020	Unknown	±500	Unknown	Unknown
ALEGrO	2020	1000	Unclear	90	Siemens
Trichur-Kerala, India	2020	1000	±320	200	Siemens
AWC, USA	2020/21	1000	±320	Multi-terminal	GE

Name	Year to be Commissioned	Power (MW)	DC Voltage (kV)	Transmission Length (km)	Converter Manufacturer
Ultranet, Germany	2021	2000	±380	340 (hybrid OHL in parallel with AC OHL)	Siemens
Tres-Amiga's, USA	2021	3x750	300	Back to Back	GE
NSN, Norway-UK	2021	1400	±525	730 (submarine)	ABB
Zhangbei phase 2	2021	Unknown	Unknown	Unknown	Unknown
Borwin4	2020+	900	Unknown	123	Unknown
Northconnect, UK-Norway	2022	1400	Unknown	655	Unknown
Viking Link UK-Denmark	2022	1000-1400	Unknown	600-700	Unknown
Greenlink, UK-Ireland	2022	500	Unknown	160 offshore	Unknown
FAB Link, UK-France	2022	1400	Unknown	2x 180	Unknown
DolWin 6	2023	900	Unknown	Unknown	Siemens
Ice Link	2024	1000	Unknown	1000	Unknown
DolWin 5	Submitting for approval	900	Unknown	Unknown	Unknown
BorWin 5	Submitting for approval	900	Unknown	Unknown	Unknown
SylWin 2	Submitting for approval	900	Unknown	Unknown	Unknown
Celtic Link	Under consideration	700	Unknown	700	Unknown

5 Grid Limitations

Traditionally with LCC HVDC there have been issues with grid interaction in terms of requiring a strong point of connection to ensure commutation of the thyristor valves, and management of harmonic distortion to the network. VSC technology can work at low short circuit levels, or indeed in islanded network. VSC schemes also produce significantly less harmonics than the LCC technology.

Requirements on HVDC schemes at low fault levels, islanded operation, harmonic distortion, fault ride through, P-Q and V-Q capabilities etc. amongst other aspects of design requirements can be comfortably achieved by VSC technologies. Although any short circuit level can be accommodated by the VSC technology, an aspect that may be overlooked is the ability of a controller to cope with a wide range of network strengths.

Due to connection of remote intermittent sources being a driver for VSC technology, the end of the HVDC scheme that typically sends power could be subject to a wide range of short circuit levels. As the network strength changes the required speed of response from any scheme would also differ. This can impact the tuning of the VSC controller.

As more power electronic are introduced to the network there is an ever increasing likelihood that there will be some adverse interactions between the different controllers. As a scheme increases in size the impact of these interactions also increases. Where a number of schemes are connected in close proximity there may be a requirement to perform detailed studies with HVDC control replicas to ensure no adverse interactions exist and that the grid reacts to events in a stable manner. This phenomenon will be required to be investigated as part of the detailed design phase of any project.

As schemes increase in size, the power flow management becomes ever more important aspect of the design. The aspects of power flow management, SQSS requirements, and operational management become more relevant for a large capacity HVDC link. There are commissioned embedded links which are relevant from the perspective of power flow management [15].

6 Future Technology

There is currently significant effort and investment being put into developing HVDC technologies. This is due to the global shift towards non-conventional generation (typically located distant from load centres) and the push towards greater interconnectivity.

In terms of hardware, there is a drive towards increasing the available power throughput by: achieving greater power density from each submodule; increasing the available voltage rating both in terms of converters and conduction medium (be it cable or overhead line). Further to this, there is research into different topologies, technology mixes (i.e. combining LCC and VSC in the same scheme) and how to implement DC grids (a key aspect being the development of DC breakers).

Best Paths is an EU funded project which has the objective of overcoming the challenges of integrating renewable energies into Europe’s energy mix. It aims to develop novel network technologies to increase the pan-European transmission network capacity and electricity system flexibility [17]. Although none of the project’s objectives directly deal with equipment ratings, the aspects looking into integration of HVDC links within AC meshed networks may feed into the design of Eastern Link HVDC Project.

PROMOTioN is another EU funded project more focussed on HVDC for offshore grids. Again whilst none of the project objectives deal directly with developing increased equipment ratings, some of the key outcomes could feed into the design of Eastern Link HVDC Project. The specific items being: interoperability of components and initiate standardisation; recommendations for a coherent EU and national regulatory framework regarding DC offshore grids; and to develop deployment plans for HVDC grid implementation [18].

All the European suppliers whose literature was reviewed are partnered to at least one of the EU funded projects that have been mentioned. Further to this they can be seen to contribute to the work done by CIGRE and other organisations around the development of VSC HVDC solutions.

Current valve ratings/ power through are limited by IGBT voltage and current capability (around 4 kV and 2000 A). Development of higher rated devices is underway with the promise of devices in excess of 4 kV and 2000 A [19]. This will result in higher density valves allowing higher power rated schemes than currently possible (for the same voltage rating). This is likely to be available for projects starting in early to mid 2020s.

Another aspect of development underway is on higher voltage rated DC cables. Currently there are proposals for VSC projects with cable rated at ±525 kV. There is a push for higher rated cables including new technology. A 600 kV MI-PPL cable is already in use in the Western Link (note that scheme is LCC HVDC).

7 Conclusions

There were three main questions asked by the Eastern Link HVDC Project with a view to identifying the optimal solution for the East Coast Reinforcement. The work undertaken answered those questions by researching what is being offered by suppliers; identifying relevant existing and contracted schemes; investigating grid limitations; and highlighting key developments in future technology.

Is it reasonable to assume that the technology will be available to commission an offshore HVDC VSC link with a rating of 2GW with the anticipated contract placement date of around 2021-23?

Yes, a rating of 2 GW appears to be currently available on the market. Converters with a rating of 500/600 kV can meet that power requirement and there is a subsea cable available to meet that voltage. Currently there are no schemes greater than 2 GW in existence or development. However, the technology will be more mature at such power levels in 2021-23. In timescales of 2021 and beyond it is likely that power ratings of 2 GW and above become the norm rather than the exception.

Is there potential for an offshore HVDC VSC link with a rating greater than 2GW? If so, what level of capacity may reasonably be obtained?

Yes, converters capable of power transfers greater than 2 GW are already available. However, due to limited maturity in the corresponding subsea cable technology, required to achieve this power rating, there is no HVDC link currently available as a reference project. Importantly, several manufacturers claim to have developed and tested cables in excess of 650 kV, which could give a rating in excess of even 3 GW. However, these new cables have not been applied in any project.

Are there limiting grid network characteristics, for example, available short circuit level that are required to be satisfied to enable a practicable HVDC VSC link of the ratings indicated in the preceding points?

VSC technology overcomes many of the issues traditionally associated with LCC HVDC technology. One of the key advantages of VSC is that it can operate across any grid short circuit rating. Normally, the range of short circuit levels has not limited the rating of the HVDC VSC links. However, it is recommended that the range of short circuit values is provided to the manufacturer at an early stage. This will allow the scheme's controller to be specifically tuned for such a range without imposing constraints on grid operators.

If the scheme size becomes large, considerations related to power flow management, overloads and maintaining SQSS compliance for various scenarios need to be considered. These aspects will need to be addressed at an early stage and may introduce a limit to the size of the scheme. As the use of power electronics becomes more prevalent throughout the network there may be control interactions between the different devices that have not previously been experienced. The risk of this issue can be reduced by performing real time simulations using replica controls.

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