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Review on Multi-Level Voltage Source Converter Based HVDC Technologies for Grid Connection of Large Offshore Wind Farms

Jakob Glasdam, Jesper Hjerrild, Łukasz Hubert Kocewiak, Claus Leth Bak

Abstract—This paper focuses on reviewing grid connection of large offshore wind farms (OWFs) employing current state-of-the-art voltage source converter based high voltage direct current (VSC-HVDC) technologies. A brief review of the VSC-HVDC evolution is given followed by an overview of the advantages of employing VSC-HVDC for grid connection of large OWFs located remote from shore. A detailed description of the topologies is given and simulation results are presented in order to illustrate some of the main features of the most popular multi-level VSC-HVDC topology.

Based on the review it is found that there are currently three vendors of the VSC-HVDC. Furthermore, it is found that the VSC-HVDC is a promising technology for grid connection of remote located OWFs and is going to be the preferred choice for remote located OWF grid connection in e.g. the UK.

Index Terms—HVDC transmission, Pulse width modulation converters, Wind Farms.

I. INTRODUCTION

Nowadays, offshore wind penetration into the electrical grid is rapidly increasing [1],[2]. Up until now the preferred sites for the OWFs have been the ones situated close to shore within reach for transmission using HVAC cables [3],[4]. However, the current trend is to move the OWFs further from shore, which gives rise to challenges with regard to construction, installation as well as transmission of the generated energy [5].

The main limitation using the conventional HVAC solution is the required compensation of the reactive power generated by the long underground and submarine cables [6]. The HVDC system seems to be the obvious solution for longer transmission distances for grid connection of OWFs [7],[8]. Recent studies indicate that the HVDC solution is more economically feasible than the HVAC for distances above approximately 70 km to the grid connection point

[9],[10],[11]. The HVDC solution has therefore become the preferred choice for grid connection in most of the planned OWFs in e.g. the UK round 3 projects, in Germany and in Denmark [9],[10],[12].

Grid connection of an OWF using HVDC fundamentally changes the electrical environment in the OWF [5]. Detailed knowledge and understanding of the characteristics and behaviour of all relevant power system components are required in order to develop reliable OWFs employing HVDC.

There exist fundamentally two HVDC technologies: (i) The conventional thyristor-based line commutated converter (LCC) HVDC, which is a well proven technology, with the first application in 1954 in Gotland [13]. (ii) VSC-HVDC, which is a relatively new technology, which is under rapid development [14],[15],[16]. The VSC technology was initially developed for drive technologies [17]. Due to significant increase in voltage and power ratings of semiconductors such as the insulated gate bipolar transistor (IGBT), the VSC-HVDC scheme started to find applications in the late 1990s, especially where the interconnected AC networks had low short circuit level or where space was limited [18],[19],[20],[21].

The VSC offers several advantages over the LCC-HVDC scheme, as the IGBT's can be turned on/off using an electronic gate signal [19]. This offers a number of advantages including insensitivity to the strength of the AC network, black start capability, fast and decoupled control of bi-directional active and reactive power flow [6],[18],[22],[23]. Furthermore, the VSC-HVDC DC link voltage is not required to invert polarity in case of power flow reversal as in the LCC scheme, which makes it possible to use extruded polymer cables, which offers the advantages of lower weight and cost compared to the mass-impregnated cables used in the LCC-HVDC scheme [13],[24].

For high power VSC-HVDC transmission system applications, the three main topologies utilized so far are the two-level, three-level and the multi-level (ML) converters [7],[18],[25]. Whereas only the Trans Bay Cable project utilizes the merging multi-level technique [10], the two and three-level topologies have found their application in a number of installations, as outlined in Table I [10],[13],[25],[26],[27],[28]. Table I indicates that the trend in future VSC-HVDC installations is to employ the multi-level converter, which will be described in more details in section III and IV.

J. Glasdam is with DONG Energy Wind Power A/S, Kraftværksvej 53, Skærbæk, 7000 Fredericia, Denmark and Aalborg University, Pontoppidanstræde 101, 9220 Aalborg, Denmark (e-mail: jakgl@dongenergy.dk, jbg@et.aau.dk).

J. Hjerrild is with DONG Energy Wind Power A/S, Kraftværksvej 53, Skærbæk, 7000 Fredericia, Denmark (e-mail: jeshj@dongenergy.dk).

L. H. Kocewiak is with DONG Energy Wind Power A/S, Kraftværksvej 53, Skærbæk, 7000 Fredericia, Denmark (e-mail: lukko@dongenergy.dk).

C. L. Bak is with Institute of Energy Technology, Aalborg University, Pontoppidanstræde 101, 9220 Aalborg, Denmark (e-mail: clb@et.aau.dk).

TABLE I
OVERVIEW OF SELECTED VSC-HVDC PROJECTS

Installation	Installed	Manu- facturer	P_{rated} [MW]	Converter topology
Gotland	1999	ABB	50	2-level
Murraylink	2002	ABB	220	3-level
Estlink	2006	ABB	350	2-level
BorWin1 (OWF)	2009	ABB	400	2-level
Trans Bay Cable Project	2010	Siemens	400	ML
BorWin2 (OWF)	2013	Siemens	800	ML
HelWin1 (OWF)	2013	Siemens	576	ML
DolWin1 (OWF)	2013	ABB	800	ML
SylWin1 (OWF)	2014	Siemens	864	ML
South-West Link	2014	Alstom	1440	ML
HelWin2 (OWF)	2015	Siemens	800	ML
Dolwin2 (OWF)	2015	ABB	900	ML

The paper is organized as follows: Section II gives a brief overview of the advantages using VSC-HVDC for OWF grid connection, section III and IV give a review of the VSC-HVDC evolvement and a detailed description of the state-of-the-art VSC-HVDC schemes, respectively.

II. VSC-HVDC FOR OFFSHORE WIND APPLICATION

Seven grid connection of OWFs using VSC-HVDC projects are listed in Table I, where BorWin1 is the only one in operation. Hence it is evident that there is very limited experience using this technology. A large number of future OWFs, which are not listed in Table I, are considered in e.g. the UK but an HVDC vendor has not yet been decided [9].

The HVDC system is associated with a high initial cost, but the marginal cost per MV is relative low, making it advantageous to connect multiple OWFs to a common offshore HVDC hub [28], as shown in Fig. 1.

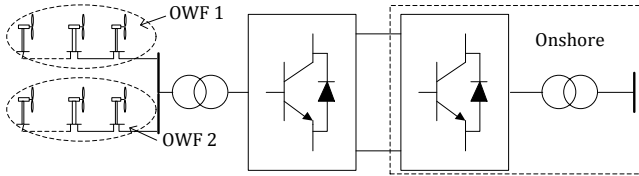


Fig. 1. Simplified schematic of the grid connection of two OWFs through a common VSC-HVDC link.

In the following are listed some of the main advantages of VSC-HVDC for OWF grid connection [9],[19],[28]:

- Most economical and technical feasible grid connection solution for transmission distances above 70 km.
- Can be connected to a weak grid and hence do not suffer from commutation failures.
- Does not require reactive power compensation as the LCC-HVDC, which alleviates the need for e.g. a synchronous reactor at the offshore platform.
- Low (or no) filter requirements.
- Lower space-requirement compared to the LCC-scheme, which is a major factor for offshore applications.
- Able to transmit power from zero to full-rating in both directions, which enables OWF start up (black

start operation) and operation at low wind speeds.

- The HVDC system decouples the onshore and offshore AC grids, hence a fault in e.g. the onshore grid is not transferred to the offshore grid, which can lower the fault ride through requirements of the WTs.
- The decoupling makes it possible to use different frequencies in the offshore and onshore grid.

III. VSC-HVDC EVOLVEMENT

The two- and three-level technologies enable switching between two or three different voltage levels to the AC terminals, respectively. The main drawbacks of these technologies include high switching losses, high dU/dt at relative high switching frequency [14], which necessitate high insulation requirements of the interfacing transformer, as well as extensive filter installations (although lower requirements than for the LCC scheme). Although the switching frequency has decreased from approximately 2 kHz to 1 kHz [13],[14] within the last decade, the efficiency of each converter station is in the range of 2 %, which is inferior to 0.7 % losses per LCC-HVDC station [14],[18].

Typically, multiple series-connected IGBTs with a blocking capability of a few kV are used in each valve in order to provide a higher blocking voltage capability of the converter and thereby increase the DC voltage [7],[18],[25]. The series connected IGBTs have to switch simultaneously (within a few μ s) in order to ensure uniform voltage distribution between the IGBTs statically as well as dynamically, which is not a straightforward task [14],[29],[30].

The needs to improve the voltage waveform and reduce switching losses have led to the development of multi-level converters [31]. The advancement of multi-level converters is considered a major step toward VSC applications for high power HVDC transmission [10]. These converters provide a number of levels in the voltage waveform, which are each only a fraction of the total AC voltage [19]. Different multi-level converters exist, including the flying capacitor and diode clamped converters. Both of these technologies have been found unsuitable for more than usually three or five voltage levels due to complex voltage balancing of the DC link capacitors [7],[30],[32],[33]. Furthermore, the flying capacitor technology requires the use of large capacitors with different voltage ratings, which limits the modularity of the converter as well as increases the footprint [34]. Another drawback of the neutral clamped converter (NPC) is the uneven distribution of switching losses between the IGBTs, which can be mitigated using the active NPC (ANPC) topology, as described in [35],[36]. In order to balance the capacitor voltages an auxiliary balancing network has been introduced, which significantly increases the complexity of the converter [30].

The need to ensure modularity, lowering the switching losses and lower the high filter requirements due to harmonics led to the introduction of the modular multi-level converter (MMC) in [31]. The MMC synthesizes a high quality sinusoidal voltage waveform by incrementally switching a high number of voltage levels. Furthermore, the switching frequency of the individual IGBTs is decreased from 1-2 kHz for the two- and three-level converters to typically 100-150 Hz in the MMC, which has reduced the losses to about 1 % at

each converter station [14],[18]. Although the losses are still higher than for the LCC-HVDC technology, the many advantages outlined in the above make the multi-level VSC-HVDC a promising technology for future OWFs located far from shore [32].

IV. WORKING PRINCIPLE OF THE MULTI-LEVEL CONVERTERS

According to Table I, there are three vendors of the multi-level VSC-HVDC. Both Siemens' HVDC Plus and ABBs HVDC Light products are based on the MMC introduced in [31] (the HVDC Light is referred to as cascaded two-level converter [14]). Although Alstom has a 25 MW VSC-HVDC prototype in operation based on the same topology as in [31], the future schemes will be based on the hybrid VSC-HVDC converter concept [17],[37]. The Plus and Light HVDC schemes will due to the similarity in their topologies be described together in subsection A, whereas the hybrid converter will be presented in subsection B.

A. Siemens' HVDC Plus and ABBs HVDC Light

The MMC is build using series connection of half-bridge sub-modules (SMs), as shown in Fig. 2.

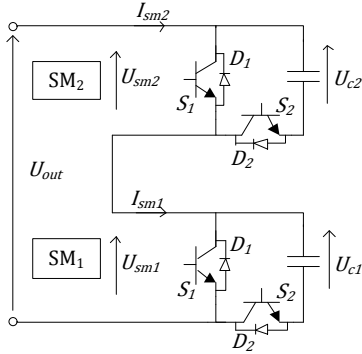


Fig. 2. Schematic of series connection of two sub-modules.

By appropriate switching of the SMs, their respective capacitances are either connected in series or bypassed in order to achieve the desired waveform of the output voltage. Series connection of the two SMs in Fig. 2 can produce three levels in the output voltage (U_{out}): For example, both SMs are inserted if S_1 is conducting in both SMs and the two S_2 are both blocking and $U_{out} = U_{sm1} + U_{sm2}$. Both SMs become bypassed and $U_{out} = 0$ V if the two S_1 are conducting and both S_2 are blocking. Depending on the direction of the current flow, the inserted capacitor either charges or discharges.

Fig. 3 shows a schematic of the MMC, with series connection of the SMs shown in Fig. 2. The phase legs are connected in parallel on the DC side; hence the DC current will be split equally between the three phase legs.

A balancing current will flow between the phase legs as the generated voltages of the three phase legs cannot be exactly equal [38]. The reactors shown in Fig. 3 are used to limit these balancing current [39], as will be described later. The phase reactors are effectively placed in series in case of a DC fault and will lower the current rise so that the IGBTs can be turned off at uncritical current levels [40].

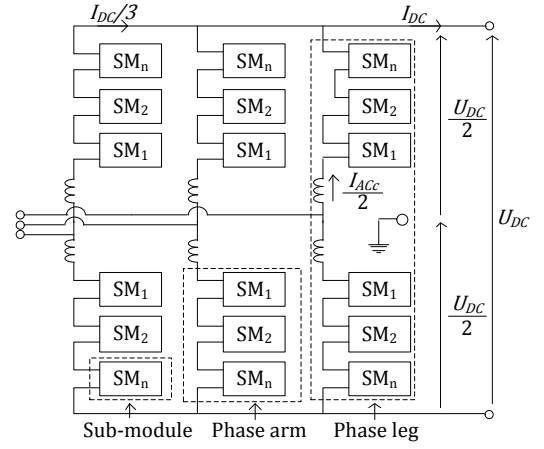


Fig. 3. Simplified schematic of the three phase multi-level converter.

The basic governing equations of the MMC can be described based on the equivalent circuit shown in Fig. 4, where the upper and lower arm valves are each represented by a controlled voltage source. The voltage of the upper (U_{i1}) and lower (U_{i2}) arm of the three phases $i = a, b, c$ can be expressed as in (1), where U_{i0} is the phase to ground voltage.

$$\begin{aligned} U_{i1} &= \frac{1}{2} U_{DC} - U_{i0} \\ U_{i2} &= \frac{1}{2} U_{DC} + U_{i0} \end{aligned} \quad (1)$$

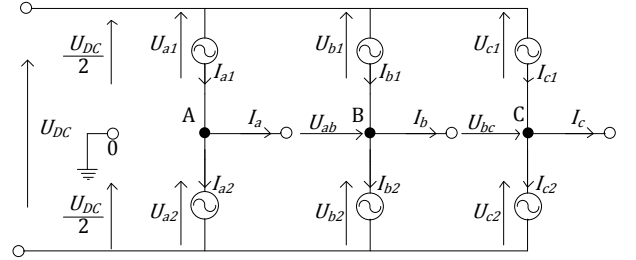


Fig. 4. Equivalent circuit of the MMC.

The equations for the DC link voltage can be expressed using KVL on Fig. 4 as in (2).

$$U_{DC} = U_{a1} + U_{a2} = U_{b1} + U_{b2} = U_{c1} + U_{c2} \quad (2)$$

Hence the three phases impress the same voltage U_{DC} . Because the converter is ideally symmetrical, the DC current will be divided equally between the three phases. Also, the phase current will be split equally between the upper and lower arms; hence the arm currents can be expressed as in (3).

$$\begin{aligned} I_{i1} &= \frac{1}{3} I_{DC} + \frac{1}{2} I_i \\ I_{i2} &= \frac{1}{3} I_{DC} - \frac{1}{2} I_i \end{aligned} \quad (3)$$

The DC component in the arm current increases the conduction losses in the MMC compared to the conduction losses in the two-level converter [41]. However, the overall losses of the MMC are lower due to the decreased switching losses compared to the two-level converter.

PSCAD/EMTDC simulation results on the system shown in Fig. 5 will be used to validate the above equations. The MMC model is composed using the build-in models of the IGBT and diode. The IGBTs are controlled in open-loop mode using phase shifted PWM with a pulse number of 3.37, as it has been shown that a non-integer value has a balancing effect on the SM capacitors [42]. Complementary switching of the

IGBTs in the upper and lower valve arms is used (i.e. when SM₁ in the upper phase arm is switched on SM₁ in the lower phase arm is switched off and vice versa).

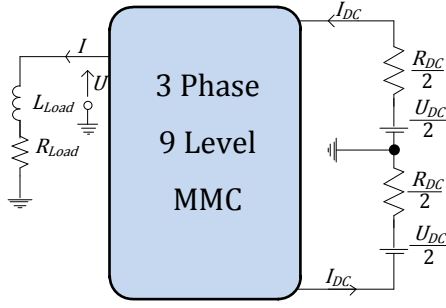


Fig. 5. Schematic of the simulation model with the following parameters: $\frac{U_{DC}}{2} = \pm 100$ kV, $\frac{R_{DC}}{2} = 100$ m Ω , RL load of $S = 140$ MVA with a power factor of $\cos(\phi) = 0.95$.

Fig. 6 shows the simulated phase voltages and currents at the converter terminal. Even with the low number of SMs, it is evident that the voltage resembles that of a sinusoidal waveform. The phase currents have little distortion even with the low number of SMs used.

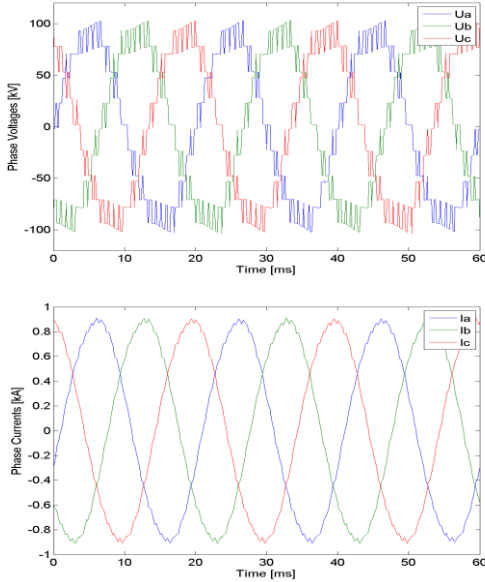


Fig. 6. Simulated phase to ground voltages and phase currents.

Fig. 7 shows the DC link voltages and phase A voltage waveforms, which confirm (1) and (2). Fig. 8 shows phase A currents. The arm currents I_{a1} and I_{a2} should according to (3) only contain the $1/3I_{DC}$ and $1/2I_i$ components. However, a large additional component is also present, namely the aforementioned balancing current, which can be seen to be of the 2nd order harmonic, which can be confirmed analytically based on a closer investigation on the MMC equivalent in Fig. 4 [38],[43],[44],[45],[46].

Closed-loop control means are used in Siemens HVDC Plus scheme in order to limit the circulating currents [47]. Different closed-loop control schemes are presented in [44],[45],[46], which effectively eliminate the circulating currents.

The balancing currents are suppressed using a parallel resonant filter located at the centre of the phase reactors and tuned at the 2nd harmonic in ABBs HVDC Light. The filter also eliminates the 3th harmonic, hence an Y/Y transformer can be used [14],[48].

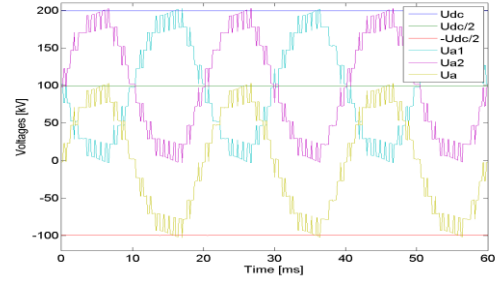


Fig. 7. DC and phase A voltages.

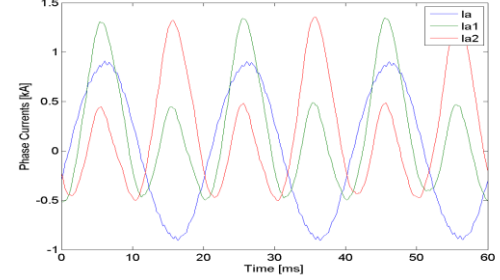


Fig. 8. Phase A currents.

A Y/ Δ transformer configuration is used in Siemens HVDC Plus scheme to mitigate the 3th harmonic [15]. Different numbers of SMs are used in the two schemes, where 200 SMs are used in each phase arm in the HVDC Plus for a DC link voltage of ± 200 kV for the Trans Bay Cable Project [10]. 38 SM are used per phase arm in the HVDC Light for a DC link voltage of ± 320 kV [14]. There are no AC filter requirements in the HVDC Plus due to the high number of SMs, whereas a small filter is included in the HVDC Light.

B. Alstom's MaxSine HVDC

As outlined in section III, the main limitations of the two-level converter is the high switching losses at relative high switching frequency, which necessitates high insulation requirements of the interfacing transformer, as well as extensive filter installations. The multi-level converter shown in Fig. 3 overcomes many of the abovementioned shortcomings, but at the expense of a twice as many semiconductors and a very large amount of distributed capacitances. Recent research has indicated the advantages of combining the features of the two-level converter and that of the MMC, and thus introducing a new hybrid family of VSC-HVDC topologies [16],[49],[50],[51],[52],[53].

The main idea behind the hybrid VSC-HVDC converters is to use a two-level converter as the main switching component with a low switching frequency and then add a relatively small multi-level converter, which is used as an active filter or wave-shaping circuit in order to eliminate the harmonics generated by the two-level converter. The hybrid converters fall into two main categories [37]: Series and parallel circuits. In the series circuit introduced in [50], the wave shaping circuit is located on the AC side of the two-level converter. The wave shaping circuit is composed of series connection of the three-level H-bridge SMs. The main drawback of this topology is the high switching losses, as the two-level converter is hard-switched [37].

Another series topology is proposed in [52], where the wave shaping circuit is located in the phase arms. The wave shaping circuit is connected to the AC terminal, when the associated

switch is on, and behaves similar to the multi-level converter shown in Fig. 3. However, there is no path for the circulating currents as the complementary switch is in the off-state. The wave shaping circuit is made up of H-bridges in order to control the currents in case of a fault on the DC side, which is a major challenge in multi-terminal HVDC systems [54]. DC faults and their associated challenges are not of the subject of the current paper and will thus not be described in further details.

The hybrid converter with the wave shaping circuit in parallel with the main phase switch was introduced in [49] and shown in Fig. 9. An H-bridge is used in each phase, connected in parallel with a wave shaping circuit, composed of half-bridge SMs, as shown in Fig. 2. The three phases are connected in series seen from the DC side; hence there will not be any balancing current flow as in the topology shown in Fig. 3. The main advantage of this topology is that the wave shaping circuit is located outside the main current path; hence the number of SMs is greatly reduced compared to the topology shown in Fig. 3, which furthermore reduces the ratings of the semiconductors and SM capacitors [37].

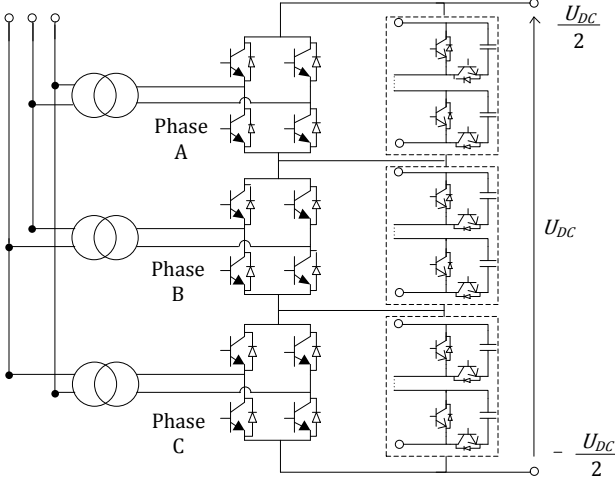


Fig. 9. Three phase representation of the parallel hybrid multi-level converter with wave shaping circuit on the DC side.

Fig. 10 will be used to illustrate the working principle of the topology shown in Fig. 9.

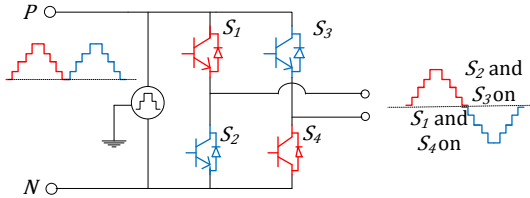


Fig. 10. Single phase H-bridge in parallel with a wave shaping circuit.

S_1 and S_4 will be switched on for the positive half-period of the 50 Hz period and the complementary switches S_2 and S_3 are on for the negative half-period. Any ripple present on the DC side will therefore be transferred directly to the AC side, which is exploited by inserting the series connected half-bridge SMs on the DC side, producing a rectified voltage sine wave as indicated in Fig. 10. The resulting AC voltage will have little distortion, depending on the number of SMs used in the wave shaping circuit. A large 6th harmonic component will be present at the DC side in the three phase converter shown in Fig. 9, which can be removed using either phase filters or

by using active techniques such as adding zero-sequence triplen harmonics to the waveforms generated by the three wave shaping circuits, which will not affect the AC side waveforms [49].

V. CONCLUSIONS

The emerging VSC-HVDC technology has previously been found to be the most technically as well as economically feasible grid connection solution for OWF located far from shore. There are few vendors of the VSC-HVDC technology and there exist no standardisation of the technology, which further has little operation experience for offshore applications. Further studies and benchmarking of the operation performance of the VSC-HVDC is required in order to further develop the technology. It is furthermore important to understand the similarities and differences between the commercial available VSC-HVDC schemes in order to improve the standardisation process of the technology.

This paper has reviewed the current state-of-the-art multi-level converter VSC-HVDC technologies for grid connection of large OWFs. Based on the review it has been found that there are some similarities between the available technologies as they all rely on a modular approach, which makes them relatively easy to scale to a desired DC link voltage.

Some of the main technical advantages of using VSC-HVDC for OWF grid connection have been highlighted and it is concluded that the VSC-HVDC technology is going to be the preferred choice for connection of remote located OWFs in e.g. the UK, DE and DK.

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