HVDC Transmission – Skagerrak 4

TET 4190 Power Electronics for Renewable Energy

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TERMINOLOGY

AC — Alternating Current
DC — Direct Current
ESCR — Effective Short Circuit Ratio
HVDC — High Voltage Direct Current
IGBT — Insulated- Gate Bipolar Transistor
LCC — Line Commutated Converter
MMC — Modular Multi-level Converter
PLL — Phase Locked Loop
PWM — Pulse Width Modulation
VSC — Voltage Sourced Converter
ABSTRACT

This report presents the two main converters used in HVDC transmission, the LCC and VSC, with regard to the new HVDC transmission line between Norway and Denmark, Skagerrak 4. The thyristor based LCC is the most common used converter in a HVDC scheme, but the transistor based VSC is maintaining several benefits. A theoretical part of the physical structure, and the advantages and disadvantages for the converters will be presented and discussed. Then a simulation in PSCAD will demonstrate the stability and behavior of the converters with respect to faults and harmonics. A comparison between the converters will be presented regarding to issues like filters, harmonics, power capacity, coordination and faults.


1 INTRODUCTION

1.1 Task description

In the summer of 2010, Statnett got a license to establish a fourth 450/500 kV DC interconnector between Kristiansand (Norway) and Denmark, Skagerrak 4. In this relation this project were established. This rapport will deal with the converter station, where the main focus will be on the difference of the converter types. The most common utilized converter today is thyristor based converters (LCC). During recent years, a new technology for transistor based converters has been developed (VSC). These two types of converters give different operation properties. Statnett will decide which of the converter technologies they will utilize under the period of acquisition. This report will give a short theoretical brief of the converters and then compare them through simulation and discussion.

1.2 The background for Skagerrak 4

The purpose of this new transmission line is to ensure and increase the power exchange with other countries. It will contribute to a more environmentally-friendly European power market, by a potential increase in exchanging renewable hydroelectric power from Norway and thermal (and wind) power from Denmark. The Danish power system is mainly based on thermal power (coal, gas and biofuel). This thermal power is difficult and slow to regulate to cope with power peaks in the grid. Thus, the electricity prices will vary a lot with the consumption. The Norwegian hydropower is on the other hand easy and cheap to regulate. In this way, the trade connection will lead to an exceptional opportunity to deliver power to Denmark when the prices there are high, and import cheap power when the Danish have power surplus. Furthermore, Skagerrak 4 will contribute to a more secure power supply and more stable electricity prices in Norway. The trading will also possibly reduce the coal-fired power. Statnett have accomplished several profitability analyses on foreign trade. They have concluded with increased power extension to other countries gives increased profitability.

1.3 About Skagerrak 4

The new connection is operated in bipolar operation with one of the existing cables (Skagerrak 3), which consists of a LCC converter. Appropriately sized LCC and VSC converters can be incorporated into a single composite (“hybrid converter”) which utilizes the benefits from both converters. The total length of the cable will be around 240 km and the power capacity will be about 700 MW. The construction work is set to 2011 – 2014 [1].
2 HIGH VOLTAGE DIRECT CURRENT

High voltage direct current (HVDC) is an electric power transmission system which utilizes direct current (DC) for transmission of high voltages in contrast to the regular alternating current (AC) systems. HVDC is economically beneficial when large amounts of power are to be transmitted for long distances, due to low electrical losses. Other beneficial factors include improved transient stability, dynamic damping of the electric system oscillations and the possibility of connecting two AC systems with different/unsynchronized frequencies [2].

2.1 Line commutated converter

The most common HVDC converters in use today are line commutated converters (LCC). LCC can be operated as rectifiers (AC-DC) and inverters (DC-AC). There are two kinds of rectifiers; uncontrolled rectifiers with diodes and controlled rectifiers with thyristors. Only the thyristor controlled converter can be operated as an inverter. Thyristor controlled converters allow adjustment of the average output voltage and direction of the power flow. During change in power flow direction the voltage polarity is changed. A thyristor is activated by a gate signal and deactivated during commutation to another thyristor. A thyristor can’t be turned off manually, like a full controlled transistor (IGBT).

A line commutated converter generates harmonic currents at the AC side and harmonic voltage the DC side. Because of high power levels, it is very important to reduce the harmonics.

A typical HVDC system is therefore equipped with two 6-pulse converters connected through a Y-Y and a Δ- Y transformer, as seen in Figure 1.

![Figure 1: 12-pulse line commutated converter [2]](image)
The output DC voltage waveform is the sum of the two 6-pulse converters connected in series at the DC side, as seen in Figure 2. The orders of harmonics in a 12-pulse converter are:

\[ h = 12n \ (n = 1, 2, 3...) \]  \hspace{1cm} (2.1)

**Figure 2: The output voltage waveform of a 12-pulse converter [2]**

At the DC side a large smoothing inductor is installed in combination with a high pass filter to limit the harmonic currents flowing into the DC line. The filter is designed to provide low impedance at the dominant 12\(^{th}\) harmonic frequency [3].

Current harmonics at the AC side is found by Fourier analysis. The Fourier components for the two 6-pulse converters are:

\[ i_{a1} \frac{2\sqrt{3}}{2N\pi} Id (\cos \omega t - \frac{1}{5} \cos 5\omega t + \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t...) \]  \hspace{1cm} (2.2)

\[ i_{a2} \frac{2\sqrt{3}}{2N\pi} Id (\cos \omega t + \frac{1}{5} \cos 5\omega t - \frac{1}{7} \cos 7\omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t...) \]  \hspace{1cm} (2.3)

Fourier components for a 12-pulse converter:

\[ i_a \frac{2\sqrt{3}}{2N\pi} Id (\cos \omega t - \frac{1}{11} \cos 11\omega t + \frac{1}{13} \cos 13\omega t...) \]  \hspace{1cm} (2.4)

Formula 2.4 shows that the Fourier analysis for the 12-pulse converter contains fewer harmonics than a 6-pulse converter, as represented in formula 2.2 and 2.3. The 5\(^{th}\) and 7\(^{th}\) harmonic contribution by the two 6-pulse converters cancel each other out. A converter with a number of pulses p has harmonics on the line current on the AC side of the order:

\[ h = pn \pm l \ (n = 1, 2, 3...) \]  \hspace{1cm} (2.5)

In a 12-pulse converter the 11\(^{th}\) and 13\(^{th}\) harmonics is the most important [2].
To reduce harmonic currents on AC side, tuned band-pass filters are used for the 11th and 13th harmonics. These filters are tuned to one or several harmonic frequencies. High-pass filters are used for the higher harmonics (23rd, 25th etc.). The high-pass filters are offering low impedance over a broad band of frequencies [4].

The converter is assumed to be connected to an ideal grid, and therefore the grid-inductance is assumed to be zero. The power flow on the DC line is controlled by adjusting \( I_d \) in Figure 1. Therefore, the reactive power consumed by a LCC increases linearly with an increase of transferred active power.

When the converter is operating in rectifier mode:

\[
Q = 1.35 \cdot V_{LL} \cdot I_d \cdot \sin \alpha
\]  

(2.6)

For a desired power transfer, the reactive power should be reduced as much as possible. To minimize the \( I^2R \) losses, \( I_d \) also should be kept as small as possible. To minimize \( I_d \) and \( Q \), it is necessary that the value for the delay angle (\( \alpha \)) is small. The minimum value of \( \alpha \) is often chosen to be between 10º and 20º.

When the converter is operating in inverter mode, the extinction angle (\( \gamma \)) for the inverter is defined in terms of \( \alpha \):

\[
\gamma = (180º - \alpha)
\]

(2.7)

\[
Q = 1.35 \cdot V_{LL} \cdot I_d \cdot \sin \gamma
\]

(2.8)

To minimize \( I^2R \) losses and the reactive power demand by the converter \( \gamma \) should be as small as possible. The minimum value of \( \gamma \) is based on the turn-off time of the thyristors [2].

Since the capacitive impedance dominates in the fundamental-frequency the harmonics, AC filters also provide a large part of the reactive power required in rectifier and inverter mode. The filter capacitor is chosen such that the produced reactive power does not exceed the reactive power consumed by the converter at minimum power level in the HVDC system. To compensate for higher reactive power consumed by the converter several power factor correction capacitors are installed [2].
Since the LCC consume reactive power they are difficult to operate when the connected AC network have a low short circuit ratio, where system voltage regulation is a problem. An AC system’s strength is determined by its effective short circuit ratio (ESCR). Traditionally, the AC system’s strength has been classified as follows:

- High, if ESCR is greater than 3
- Low, if ESCR is between 2 and 3
- Very low, if ESCR is less than 2

Usually the LCC need an effective short circuit ratio of at least 2 to operate. The ESCR is defined by:

\[
ESCR = \frac{S_{sc}-Q_{filter}}{P_{HVDC}} \geq 2
\]  

\[
Q_{filter} \approx 0.5 \cdot P_{HVDC}
\]

\[
S_{sc} \approx 2 \cdot P_{HVDC} + 0.5 \cdot P_{HVDC} \approx 2.5 \cdot P_{HVDC}
\]

\[S_{sc}\] is the three phase short circuit MVA of the AC system. \(Q_{filter}\) is MVAR of all shunt capacitors, including AC filter capacitors connected at the converter station AC bus. \(P_{HVDC}\) is the rated DC power. Short circuit rating is supplied from mechanical (rotating) inertia. A synchronous machine has a transient reactance \(x'\) of about 0.2, meaning \(S_{sc,m} \approx 5 \cdot S_{n,m}\). Due to the power loss in the transformer, the approximate short-circuit rating of a synchronous machine is \(S_{sc,m} \approx 2.5 \cdot S_{n,m}\). The result is therefore that the LCC converter needs a generator, or rotating mass, with the same rating nearby [5].

### 2.2 Voltage sourced converter

A voltage sourced converter (VSC) is an important power electric device in power transmission and distribution such as HVDC. In comparison with traditional line commutated thyristor based converters (LCC) the VSC, which utilizes modern IGBTs, is self commutated. Basically, the difference between LCC and VSC is that VSC need components that can turn off the current and not only turn it on as is the case for LCCs. Since the current can be turned off there is no need for a network to commutate against.

Regular VSC converters for HVDC applications, which is based on 2- or 3-level technology (PWM), enables switching between respectively two or three different voltage levels to the AC terminal of the converter. There are also VSC converters which are based on multi-level modulation (MMC), which enables switching between many voltage levels.

The main advantage with VSC is the capability to rapidly control both active and reactive power independently of each other, to keep the voltage and frequency stable.
The use of filtering varies with the different types of VSC. While PWM gets some distortion due to the difference between desired and actual waveform, the MMC topology has no need for filtering since the difference between desired and actual waveform is small. This is described more extensively under each topology.

During change of power direction the VSC topology change the current direction, unlike LCC which change the voltage polarity. This means that in VSC the voltage polarity on the DC side is always the same. This makes the establishment of multi-terminal solutions easier. A multi-terminal DC grid makes it possible for several nodes to extract/supply power from the same transmission line, which is very beneficial in i.e. an off-shore wind mill park.

To this date, the DC power levels and voltages are lower for VSC than LCC based HVDC. VSC is for now mostly designed for networks in the low power range, where the system with highest power rate is 400 MW. Main manufacturers, such as Siemens and ABB, confirm the feasibility of 1200 MW, +/- 320 kV HVDC VSC [6].

### 2.2.1 Voltage sourced converter with pulse width modulation

The first commercial project with this VSC topology was realized in 1999. The control of the voltage source converter utilizes pulse width modulation. Pulse width modulation is a flexible way of controlling the output voltage waveform where the desired fundamental and harmonic voltages are controlled by modulating the width of the voltage pulses. The AC output voltage is created by switching very fast between two or three fixed voltages of the constant DC voltage (bipolar- and unipolar switching). The output waveform is then filtered to produce a specified fundamental component of controllable magnitude as well as eliminate the low-frequency harmonics. The fact that PWM allows independent control of the reactive power in both terminals improves the dynamic voltage stability. Since it has control of the reactive power it doesn’t require reactive power compensation.

![Figure 3: Principle of control of converters based on two-level technology [9]](image)

Figure 3 shows how VSC with PWM can be controlled with two-level technology (bipolar switching). As the figure shows the realized voltage differs between two voltage levels, \( +U_d/2 \) and \( -U_d/2 \).
and \(-U_d/2\), and the width of these voltage pulses controls the AC output voltage. A converter with three-level technology switches between \(+U_d/2\) and 0 in the first half period, and between \(-U_d/2\) and 0 in the second half period. Figure 3 also shows that each IGBT have a diode connected in anti-parallel. This is to ensure that the bridge voltage has only one polarity, while the current can flow in both directions. The diodes in the VSC bridge constitutes an uncontrolled rectifier when the IGBTs are turned off. The diode will therefore provide sufficient reverse voltage withstand capability. These diodes have to be designed to withstand fault-created stresses [7].

The desired waveform at the AC terminal is a sine wave. But, since the desired waveform at the AC terminal cannot be adjusted in terms of magnitude, PWM is used to approximate the desired waveform. However, the difference between the implemented and the desired voltage waveform is an unwanted distortion which has to be filtered.

In a PWM converter the phase-to-phase voltage will contain only odd-harmonic orders other than those multiples of three. The harmonic spectrum is determined by two factors, \(M_a\) and \(M_f\). \(M_a\), which is the ratio of the peak amplitude of the line-to-line voltage (\(V_{LL}\)) to the DC voltage (\(V_d\)), determines the modulation ratio. If \(M_a \leq 1.0\), the fundamental-frequency component in the output voltage varies linearly with \(M_a\).

\[
M_a = \frac{V_{LL}}{V_d}
\]  

(2.10)

The factor \(M_f\), which is the ratio of the modulation frequency (\(f_m\)) to the output frequency (\(f_1\)), determines the harmonic spectrum for a given modulation pattern.

\[
M_f = \frac{f_m}{f_1}
\]  

(2.11)

\(M_f\) should be a multiple of three to cancel out the most dominant harmonics. A sufficiently large value of this ratio will reduce all the low-order harmonics to be within the specified limits. However, a high-frequency ratio will cause high switching losses. As the low-order harmonics normally will be suppressed by PWM topologies, these filters will be tuned to higher frequencies and will therefore be cheaper and more compact than the filters for LCC topologies [2][7].

### 2.2.2 Voltage sourced converter with modular multi-level converter

Regular VSC converters are based on 2- or 3-level topology, which makes it possible to switch between 2 or 3 different voltage levels on the AC side of the converter. As mentioned before the VSC topology use PWM to approach the desired sinusoidal waveform, but it is difficult to get a clean sinus wave without using extensive filtering. The drawbacks of the afore-mentioned topology can be eliminated by using a much better approximation of the sinusoidal waveform in terms of adjustable magnitude of the voltage to the AC terminal. This is possible when using modular multi-level (MMC) converter. In this topology, the converter arms act as a controllable voltage source with a high number of possible discrete voltage steps. This results in a better
approximation in terms of adjustable magnitude of the voltage to the AC terminal. The MMC principle is shown in Figure 4, and the principle design of a MMC is shown in Figure 5 [8].

![Voltage step principle](image)

*Figure 4: Voltage step principle [8]*

![Principle design of a MMC](image)

*Figure 5: Principle design of a MMC [8]*

The converter in Figure 5 consists of six converter legs, where each converter leg consists of a series of sub-modules (SM) connected in series with each other and with one converter reactor. Each of the sub-modules contains an IGBT half bridge as switching element in parallel with a DC storage capacitor [9][10]. Each sub-module can operate in three different states, and that is:

1. Both IGBTs are switched off.
   The capacitor is charged if the current flows from the positive DC pole towards the AC terminal. Otherwise the freewheeling diode D2 bypasses the capacitor.
2. IGBT 1 is on and IGBT 2 is off.
   Full module voltage is applied to the terminals due to the capacitor.
3. IGBT 2 is on and IGBT 1 is off.
   This state ensures zero applied voltage to the terminals, and the voltage in the capacitor remains unchanged.

By connecting sub-modules in series it is possible to individually and selectively control each of the individual sub-modules in a converter arm. The total voltage of the two converter arms in one phase unit equals the DC voltage, and by adjusting the ratio of the converter arm voltages in one phase module, the desired sinusoidal voltage at the AC terminal can be achieved [10].

If a fault occurs in one of the sub-modules, it can easily be bypassed by a high-speed switch, which is integrated in the IGBT module. This is one of many benefits to the MMC topology. The bypass switch is not included in Figure 5. By installing some extra module in series in each converter leg, which normally is short-circuited, provide a fail-safe function [9].
2.3 Control of HVDC converters

An LCC HVDC system is usually operated to maintain a constant DC current and DC voltage. The pole control produces control characteristics, by selecting the minimum value among the outputs of constant current (CC), constant voltage (CV) and constant extinction angle (CEA) controls. Extinction angle control is needed to avoid commutation failures in inverter operation, which occur if the commutation process does not complete a certain time before the thyristor becomes forward biased.

Figure 6: Control blocks for LCC converters [11]

In a hybrid system with both LCC and VSC converters, the control system can be designed differently. As an example, the LCC rectifier operates in current control mode, while the inverter’s LCC operates in extinction angle control mode.

Figure 7: Control blocks for VSC converters [11]

The VSCs magnitude and angle driving signals will be issued based on VSCs capacitor voltage ($V_{dc}$) mismatch, terminal voltage ($E_t$) mismatch (which respectively generate VSCs active and reactive powers) and terminal’s direct and quadrature axis components of voltage [11].

A dq-transformation is a mathematical transformation used to simplify three AC quantities to two DC quantities. The d and q errors are used to generate the corresponding voltage orders ($V_d$ and $V_q$) through a decoupled controller block. These are converted into a modulation index magnitude ($m$) and phase ($\phi$) signal. A phase locked loop (PLL) is used to synchronize with the AC network and generates the synchronization angle signal ($\theta$) which is used to generate the firing pulses for the IGBT devices of the VSC [12].
3 PSCAD SIMULATION

PSCAD is an electromagnetic time domain transient simulation program. The intended use of this program is to evaluate the waveforms given by the different HVDC topologies. Because of the complexity of the VSC with MMC topology, VSC is represented only by the PWM topology. In order to compare VSC and LCC, the simulation describes a focus on harmonics and fault current.

The fault is applied on the inverter side on both converters in this simulation, and the fault is localized on the AC-bus near the inverter. The applied fault-time is 50 ms, and the different faults which are simulated are 1-phase fault (between phase C and ground) and 3-phase fault. Only the most interesting discoveries will be presented here.

3.1 LCC fault simulation

The theory claims that for faults near the inverter of a LCC HVDC system, will lead to a decrease of the DC voltage at the rectifier, which may cause the current not to completely commutate from one valve to another, and then lead to a short-circuit. This can easily be observed from the simulation of the LCC converter in Figure 8 on 1- and 3-phase fault. It can also be observed that the DC current on the inverter side rise drastically before the control brings it back down. The DC-voltage and current on the rectifier side is influenced by the fault phenomenon on the inverter side.

Figure 8: LCC faults
The voltage on phase C (1-phase fault) goes to zero in the fault period, and the other phases get a slightly increased voltage during this period on the inverter side. The rectifier AC-voltage seems just slightly influenced by the fault, with a small disturbance on the three phases, as seen in Figure 8.

DC fault is not simulated in this project because this type of fault is fairly rare in a HVDC transmission system. If a DC fault should occur, the converter will not draw any fault current from the AC system, as the fault current will extinguish very quickly due to the unidirectional aspect of the thyristor valves. Typically the control system reduces the DC current within milliseconds after its initial increase [13].

### 3.2 VSC fault simulation

![Figure 9: VSC faults](image)

Unlike the LCC converter, a VSC converter does not fail commutation during an AC fault. The VSC will still be able to feed an amount of power during the fault, depending on the voltage reduction on the AC terminals. In addition, the VSC will be able to recover faster than the LCC converter once the fault is cleared on the AC side. As seen in Figure 9, the PSCAD simulations for 3-phase fault show that the voltage will increase by 4 times per unit value. The voltage increase occurs as a consequence of inaccurate settings for the control. The control settings are accurate enough for 1-phase fault because the fault current is smaller than the 3-phase fault current. The simulation results for 1-phase fault shows that the VSC recover faster than the LCC.
A large weakness for the VSC in fault situations is the DC faults. During the time it takes to clear a DC fault, it is fed from all the AC systems connected to the DC line through the VSC diodes. This results in a large fault current drawn from the AC system. However, the fault current will be reduced due to phase reactors, DC smoothing reactors and line impedances. During this time the voltage at the connected AC systems will be reduced, depending on the strength of the AC system and location of the fault. However, DC fault is not simulated for VSC because it is very rare in a HVDC transmission system [13].

### 3.3 LCC harmonic simulation

![Figure 10: Harmonic components in LCC](image)

In chapter 2.1 it was presented that in a LCC converter the current harmonics would be of order $h = pn \pm 1$ ($n = 1, 2, 3...$), for a converter with pulses $p$. By observing Figure 10, the theory fits well with practice. Note that the harmonics for the 6-pulse converter is just included for comparison.

### 3.4 VSC harmonic simulation

![Figure 11: Harmonic components in VSC](image)
In chapter 2.2.1 it was presented that in a PWM converter the phase-to-phase voltage will contain only odd-harmonic orders other than those multiples of three. The harmonic spectrum is determined by two factors, $M_a$ and $M_f$. When values from the simulation are put into the formulas for $M_a$ and $M_f$, the results will be as follows:

\[ m_a = \frac{V_{LL}}{V_d} = \frac{103.92kV}{120kV} = 0.866 \]

\[ m_f = \frac{f_s}{f_i} = \frac{1.98kHz}{60Hz} = 33 \]

The result shows that the amplitude modulation ratio $M_a \leq 1$, i.e. the fundamental-frequency component in the output voltage varies linearly.

In theory, important harmonics observed for three-phase voltage source converter is at:

\[ m_f \pm 2 \quad 2m_f \pm 1 \quad 3m_f \pm 2 \]

When this is compared to the Figure 11, it is observed that this fits perfectly well.
4 A COMPARISON OF THE ALTERNATIVES

The intention of this chapter is to compare LCC and VSC regarding the Skagerrak 4 connection. The planned power rate of the Skagerrak 4 connection is 700 MW 450/500 kV, which is higher than any yet installed VSC system. Thus, VSC topology has no formal records of reliability for this level of transmitted power. The manufacturers, however, claim that with today’s technology VSC is able to transmit 1 200 MW +/- 320 kV. The power rate is no limitation to the LCC.

The new Skagerrak 4 connection is going to be operated in bipolar operation with an existing connection which utilizes LCC. If Skagerrak 4 will use a VSC system this would require some additional challenges. Because, during change in power direction the LCC system switch polarity of the voltage and VSC switch the current flow direction. This would therefore require a switching station where the phases are switched. The control of this system would be as the hybrid system. Such a system utilizes benefits from both converters. An example is that the reactive power control of VSC can be transferred to the LCC system, and therefore the amount of filters in the LCC system can be reduced.

LCC will absorb reactive power, unlike VSC which it can operate at any leading or lagging power. The consumption of reactive power for LCC varies with the amount of active power conversion, and therefore the VAR compensation needs to be adjusted as the load varies.

As mentioned in chapter 2.1, the 12-pulse LCC need filters to reduce the harmonics, especially the 11th and 13th harmonics. In use of PWM switching or multi-level configurations in a VSC scheme, the filter requirements are reduced.

Since the LCC topology requires large filters the site area will be relatively large compared to the VSC topology. However, the size might not be a problem for this converter station.

Unlike the LCC converter, a VSC converter does not fail commutation during an AC fault. VSC will therefore be able to recover faster than the LCC converter once the fault is cleared on the AC side.
5 Conclusion

The new HVDC interconnector between Norway and Denmark will utilize either a LCC or a VSC based converter. Their operation properties consist of various advantages and disadvantages. The LCC is the most common converter in HVDC transmission. It can be delivered up to almost any power capacity size, and are a cheaper converter compared to the VSC. On the other hand, the LCC consumes reactive power and are more exposed for commutation failures. Moreover, it generates low harmonics and is dependent of large filters to provide the harmonic standard level. The simulation in PSCAD have shown that the LCC generates low harmonics, where the 11th and 13th are the most important. The VSC’s main advantage is the ability to generate lagging or leading reactive power, this permits them to operate and provide voltage support to the AC network. The fault simulation also shows that during a fault near the inverter, the VSC is able to recover faster than the LCC, because it’s not exposed of commutation failure. VSC’s mainly disadvantages includes higher costs, sensitivity to DC side faults, higher power losses due to the high frequency of switching and smaller ratings compared to conventional LCC.

If a VSC is selected for Skagerrak 4, it will be controlled by a hybrid topology employed of a LCC and VSC converter. This results in a more complex scheme, but combines benefits of both converters. The VSC’s fast dynamic response to reactive power demands has a unique capability of working under even lower short circuit ratios (SCR), where the LCC would not be able to operate. Even if the VSC consist of several benefits, it may not necessarily be the optimal solution. The grid conditions, economical aspect and operating properties must be taken into consideration.
REFERENCES


