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Skagerrak
The Next Generation

HVDC and Power Electronic Technology
System Development and Economics

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Abstract – After nearly four decades of operation, the Skagerrak HVDC transmission system, interconnecting Norway and Denmark, continues to expand and evolve. The Norwegian power supply is predominately hydroelectric. During the first decade of Skagerrak operation, the Danish power supply was mainly thermal. More recently, however, penetration of wind generation in Denmark has reached very high levels. This trend has influenced further system development including that of the Skagerrak HVDC interconnection.

Skagerrak 1 & 2, rated ± 250 kV, 500 MW, were commissioned during 1976-77. Skagerrak 3, rated 350 kV, 500 MW, was added in 1993. A number of refurbishments and upgrades followed. Skagerrak (SK) 1, 2 and 3 utilize current-sourced, line-commutated converters (LCC). System economic benefits favored further expansion of Skagerrak in 2014. A number of system considerations influenced the overall most economic choice of converter technology. These included simplified reactive power compensation, improved voltage stability, black start capability and mitigation of multi-infeed effects from other HVDC links in the region. As a result voltage-sourced converter (VSC) technology was optimally selected for Skagerrak 4, rated 500 kV, 700 MW.

This paper describes the Skagerrak HVDC system focusing on its most recent expansion, SK4, which increases total transmission capacity to 1700 MW. Bipolar operation of SK3 LCC converters with SK4 VSC converters is discussed. This includes maximizing efficiency, minimization of system unbalance current, power reversal and emergency power control. Asymmetrical operation of SK4 in order to operate in this mode is illustrated along with its impact on main circuit design, insulation coordination and switching arrangements.

INTRODUCTION

The Skagerrak HVDC transmission system interconnects Norway and Denmark over a submarine cable crossing of the Skagerrak Strait. The Norwegian and the Danish grids operate asynchronously. The Norwegian terminal, Kristiansand, is located near the southernmost coast of Norway. The Danish terminal, Tjele, is located about 100 km inland in the Jutland Peninsula. The system operators in Norway and Denmark are Statnett and Energinet.dk respectively. With the recent addition of SK 4, rated 700 MW, the total capability of the interconnection, comprised of four poles, has risen to 1700 MW. Main system data for the Skagerrak HVDC System is given in Table I.

		Poles 1 & 2	**Pole 3**	**Pole 4**
Power	MW	2 x 250	500	700
DC voltage	kV	250	350	500
DC current	A	1000	1430	1400
Converter technology		LCC	LCC	VSC
AC voltage (Kristiansand, NO)	kV	300	300	400
AC voltage (Tjele, DK)	kV	150	400	400
DC sea cables	km	127	127	140
DC OVHD line	km	113	113	-
DC land cable	km	-	-	104
Commissioning year		1976 - 1977	1993	2014

Table I. Skagerrak main system data

Power generation in Norway is predominately hydroelectric. During the first decade of operation power generation in Denmark was mainly thermal. Initially the Skagerrak interconnection was primarily used to facilitate economic generation dispatch. It also allowed for emergency system support, including fast power reversal, following contingencies. In subsequent years the penetration of wind power in Denmark steadily increased. In recent years, net wind generation output in Denmark can occasionally exceed the system load. Rapid changes in net wind production can also occur. This has led to new market uses for Skagerrak. The interconnection enables hydro generation and reservoir storage in Norway to be used to help balance wind generation in Denmark. Consequently, the number of scheduled power reversals has increased substantially.

Each Skagerrak terminal is located at or near the periphery of its respective network without major conventional generation nearby. Adequate short circuit capability is necessary for proper HVDC system operation. If the effective short circuit ratio, ESCR, becomes too low, a number of issues can arise. These include larger voltage steps at AC filter switching, voltage instability, low-order harmonic resonance, degraded dynamic performance and high dynamic overvoltage at load rejection. This is especially true in Denmark with the high penetration of wind generation in Jutland. Furthermore, with other HVDC interconnections in the area, e.g. Konti-Skan and NorNed as shown in Figure 1, multi-infeed effects can adversely affect voltage instability and dynamic performance. With relatively weak system connections and low mutual impedance between stations, a disturbance on one system can induce a disturbance on a neighbouring system. These disturbances could include induced commutation failure.

Energinet.dk has added a number of synchronous compensators to support the higher levels of wind generation and power transfers. More system upgrades including synchronous condensers would have been required in both Norway and Denmark if SK 4 were to utilize conventional LCC. Using VSC for SK 4 meant no additional reactive power compensation would be required. The SK 4 converters absorb no reactive power. They can be controlled to regulate AC voltage or reactive power within their reactive power capability limits similar to a synchronous machine. Therefore, less system upgrades would be needed to accommodate the additional 700 MW transfer capability. Additional operational benefits would also be realized with VSC. Benefits include improved AC voltage regulation, better reactive power balance, black start [Ref. 1] and mitigation of dynamic overvoltage. These factors were taken into account in the overall economic evaluation and choice of converter technology. With such benefits readily apparent, the issue then became how to integrate the new VSC based pole in a hybrid configuration with the existing LCC poles.

Figure 1. Skagerrak, Kont-Skan and NorNed HVDC links

DC SYSTEM CONFIGURATION

SK 1 & 2 originally operated in a bipolar configuration. Thus the flow of current through the electrode stations was normally limited to just the bipolar imbalance current. The original configuration was changed, however, with the addition of SK 3. At that time SK 1 & 2 were reconfigured so that the two original poles had the same DC voltage polarity and the same DC current direction, a.k.a. homopolar mode or parallel operation. SK 3 was configured to operate with the opposite DC voltage polarity and opposite DC current direction as SK 1 & 2. In other words, SK 1 & 2 were operated as one pole with parallel converters in a bipolar configuration with SK 3. The DC current direction from SK 3 thereby opposed that from SK

1 & 2 partially offsetting the ground electrode current. Due to the different converter current ratings, it was not always possible to balance the pole currents, e.g. during high power transfer. The configuration changed again with the addition of SK 4. SK 1 & 2 reverted to their original bipolar configuration, and SK 3 was paired with SK 4 as a second bipole as depicted in Figure 2. The SK 4 525 kV DC cables utilize mass-impregnated oil and paper insulation. The SK 4 cable extends for the entire length of the transmission including on land whereas SK 1, 2 and 3 have overhead line sections in Denmark.

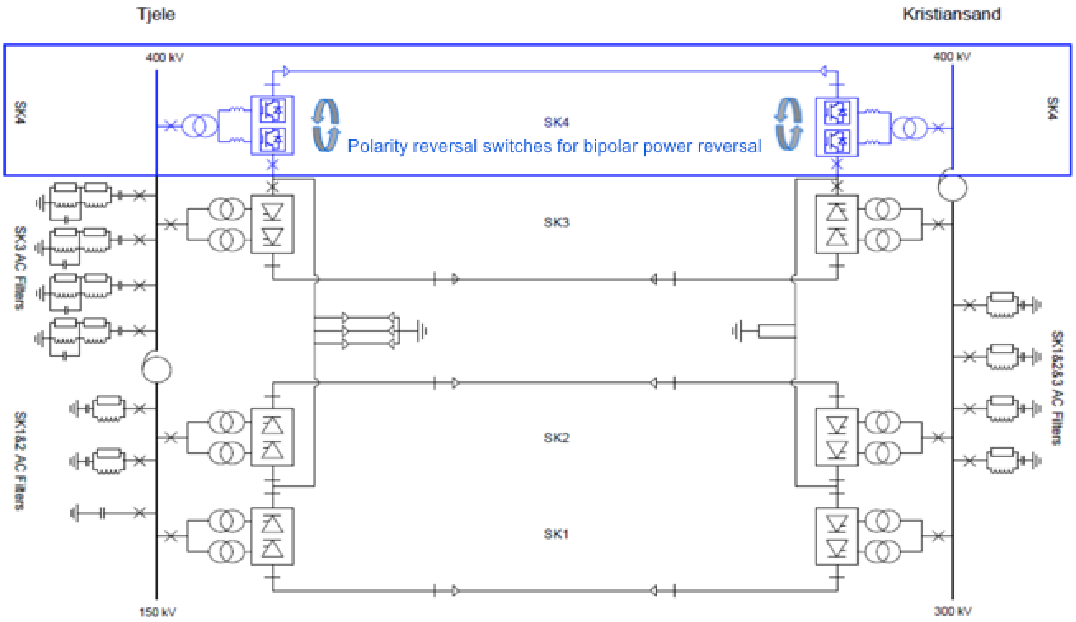

Figure 2. Skagerrak simplified single-line diagram

Combining LCC and VSC in a hybrid bipolar arrangement is not as straightforward as it may appear from Figure 2 at first glance however. There are two main differences to consider. These are power reversal and converter configuration. Power reversal with conventional LCC is accomplished by converter polarity reversal, whereas power reversal with VSC is by current reversal. In the former, current always passes in the same direction. With the latter, converter polarity always remains the same. Prior to Skagerrak 4, almost all VSC-based HVDC links were configured as a symmetrical monopole. Most LCC based HVDC links, however, utilize asymmetrical converter connections operating in either monopolar or bipolar modes. The converters in a symmetrical monopole are connected pole-to-pole. With a symmetrical monopole configuration two cables, each rated at half the converter voltage, are required. Furthermore, there is no DC potential on the converter transformer or converter AC bus. The DC pole voltage on each pole is half the voltage across the converter. One pole is positive the other pole is negative. Asymmetrical operation of VSC or LCC converters enables use of only one high voltage cable. The cable is rated for the full converter voltage. There are other impacts due to asymmetrical operation. A DC voltage component is added to the converter transformer and converter AC bus insulation requirements. Voltage measurements on the converter side of the transformer require use of a voltage divider rather than a CVT.

In order to connect SK 4 in a bipolar configuration with SK 3, SK 4 had to be configured as an asymmetrical monopole. This meant that one side of the converter is connected to the DC neutral bus, and the full converter DC voltage appears on the pole side. If nothing else were done, this would have meant that the pole DC pole currents would offset one another for one power direction but add together in the other power direction. To eliminate this problem, the SK4 converters were designed with full DC voltage insulation level on both sides, and equipped with fast dc polarity reversing switches for scheduled power direction reversals. [Ref. 2] Figure 3 illustrates the converter switching arrangement for SK4. This includes the DC-side switching for converter polarity reversal and AC-side switching for converter and cable energization. The cable termination at one end is equipped with switchable discharge resistor. A resistive grounding circuit is also provided on the AC side to ensure a current zero crossing when tripping for converter AC bus phase-to-ground faults.

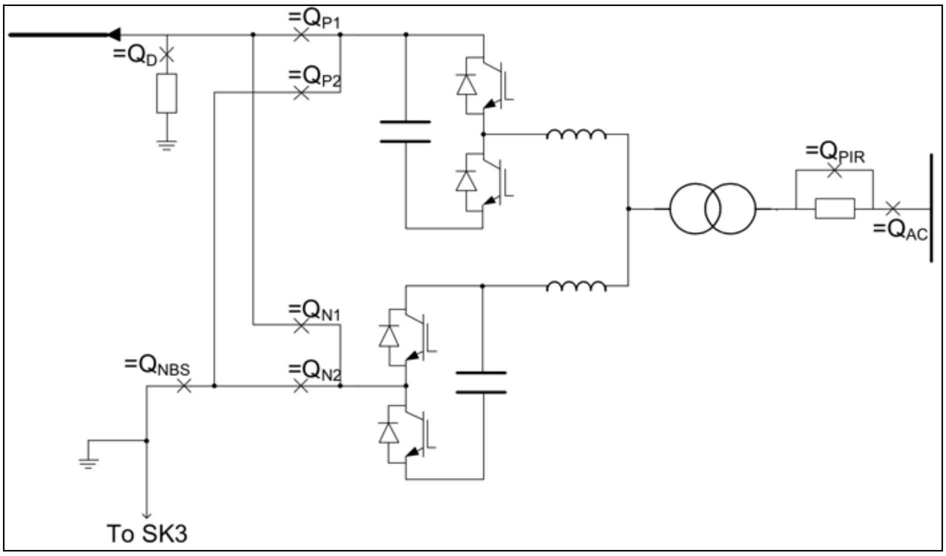

Figure 3. Skagerrak 4 polarity reversal switching arrangement

The sequence for normal power reversal of SK4 in hybrid configuration with SK3 is as follows:

1. Reduce power level to minimum or zero.
2. Stop power transmission
3. Disconnect SK4 from AC grid
4. Disconnect converter from DC cable and neutral bus
5. Discharge the DC cable
6. Reconnect converter with opposite polarity on the neutral side
7. Open cable discharge circuit
8. Reconnect converter with opposite polarity on the cable side
9. Energize the converter and cable from the AC grid through the pre-insertion resistor
10. Bypass the pre-insertion resistor
11. Start power transmission
12. Increase power transfer to desired level

ADDITIONAL CONTROL FUNCTIONS FOR HYBRID LCC-VSC OPERATION

Operation of SK 3, LCC, together with SK 4, VSC, in a hybrid bipolar configuration benefits from some special control functions. The most obvious additional control function is the polarity reversal switching of SK 4 to allow power reversal without cumulative electrode current. Another special consideration is to minimize earth current with the dissimilar pole ratings. A bipolar power control is used to minimize the electrode current taking into account the measured DC pole voltages and converter current limitations. The capabilities of the VSC converter to reverse current and operate at zero power are also used to be able to operate the bipole below the minimum power rating of the LCC converter. Aside from that, the bipole control provides automatic compensation upon loss of a pole as is generally the case with a bipolar transmission link.

Skagerrak is also equipped with a fast emergency power control, EPC, which can rapidly runback the dc power transfer or even reverse the power direction within seconds. In the event that the EPC calls for power reversal, polarity reversal switching of SK 4 is not used. In that case, the consequential addition of pole 3 and pole 4 currents in the electrodes is allowed but only for a limited period of time. Once the networks have stabilized, the system can revert to its pre-disturbance power schedule. If this is not possible within a reasonable time due to system conditions, power reversal can be done in the normal way in order to eliminate earth return current once the AC systems have readjusted to their new operating conditions.

MAIN CIRCUIT DESIGN

Some key points pertaining to the main circuit design are listed below:

- Cascaded two-level, CTL [Ref. 3], converter cells are used with 30 series-connected cells per valve arm. Four cell groups are stacked and suspended from the valve hall roof trusses.
- Single-phase transformers are used, grounded wye connection with LTC on the primary or network side, delta connection on the secondary or converter side.
- Pre-insertion resistors with bypass circuit breakers are used on the network side of the transformers for damping converter and cable energization transients.
- An earthing breaker with grounding resistor is provided on the network side of the transformer to ensure a current zero at tripping for converter side AC bus phase-to-ground faults.
- A small AC harmonic filter is provided for SK4 but only in Kristiansand since it is the only converter connected to the 400 kV AC bus at that terminal. At Tjele the SK3 filters are connected to the 400 KV bus and provide sufficient filtering also for SK4.
- Two arresters are provided on the converter ac bus due to distance between the transformers and the valve arm reactor hall.
- AC grounding switches are provided on each side of the transformer, in the reactor hall and in the positive and negative valve halls.
- PLC and RI filters are provided on the AC converter bus.
- A voltage divider is used for potential measurement on the converter bus rather than a CVT due to the presence of DC potential with the asymmetrical converter connection. CVT is used on the network side for voltage measurement.
- The valve arm reactors are tapped for connection of 2nd harmonic filter capacitor provided due to use of 3rd harmonic PWM for boosting converter power.
- Optical current transformers, OCT, are used for measuring valve currents.
- Each converter CTL cell has capacitor voltage supervision.
- DC grounding switches are provided in the valve halls and in the DC yard.
- High frequency damping filters are provided on the DC side of the converters.
- A DC capacitor bank, connected pole-to-neutral is provided for independent STATCOM operation.
- Polarity reversal switching is provided in the DC yard.

- Smoothing reactors are installed in both pole the pole and neutral connections.
- Pole arresters, voltage dividers and OCTs are connected on each DC bus.
- A disconnect switch with grounding switch on each side is provided for connection/ disconnection of the cable.
- An arrester and voltage divider is connected at the cable connection.
- A switched cable discharge resistor is provided at the Kristiansand end only.
- A DC surge capacitor is connected to the neutral bus to limit the neutral voltage during pole to ground faults.
- The voltage ratings and insulation levels for SK 4 external interfaces are indicated in Table II. Overvoltage protection is provided by strategically-placed surge arresters with adequate protective margin.

Ratings		**AC Yard**	**DC Yard**	**Cable Term.**	**DC Neutral**
Nominal	kVac	415	-	-	-
	KVdc	-	500	500	1.5
Rated	kVac	390-440	-	-	-
	kVdc	-	502.5	502.5	10
	kVdc pk	-	525	525	-
LIWL	kV (ph-g/across)	1425	1140	1050	125
SIWL	kV (ph-g/across)	1050	958	958	109
LIWL xfmr	kV (ph-g)	1300			

Table II. Skagerrak 4 voltage ratings and insulation levels, Tjele

STATION LAYOUT

The AC and DC switchyards for the SK 4 converters are located outdoors. The valves, valve arm reactors, and associated equipment are located indoors. The reactor hall is located between the positive and negative polarity valve halls. AC side and DC side connections are via wall bushings. The AC terminal is connected to the customer's 400 kV switchyard. The high voltage pole connection is made to the 525 kV DC cable outdoors in the DC switchyard. The DC neutral bus is connected to that of SK 3. Figure 4 illustrates the station layout with its outdoor AC and DC switchyards and converter building. Figure 5 shows the station overview for the Skagerrak Tjele terminal. The inset photo depicts the SK 4 converter building with the AC switchyard in the foreground.

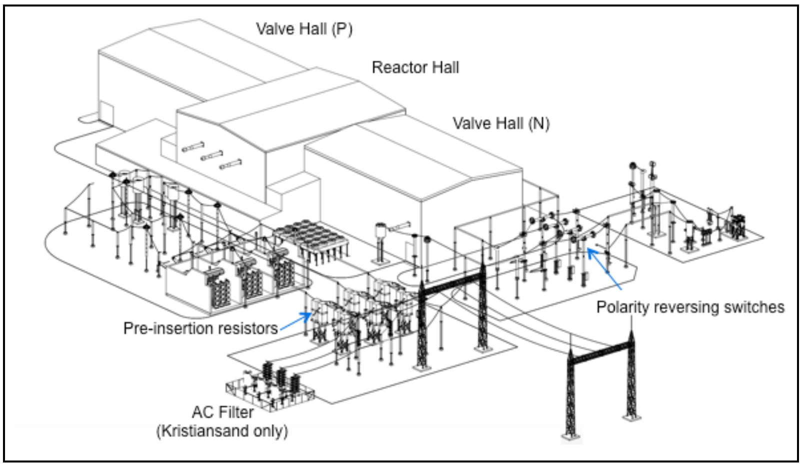

Figure 4. Skagerrak 4 station layout

Figure 5. Skagerrak Converter Station, Tjele Terminal

CONCLUSION

Skagerrak 4 has achieved several milestones. It has established 500 kV as the highest DC voltage to date for VSC-based HVDC transmission. It is the first hybrid application with VSC and LCC used for different poles. SK 4 also demonstrates that higher power transfers are possible with less system reinforcement when the network is relatively weak. The inherent characteristics of the voltage sources converters eliminate the need for reactive compensation, improve voltage stability and simplify overall system operation. SK 4 experience has demonstrated that higher power transfer levels are now possible with VSC-based HVDC systems. Power transfer capability comparable to that of a long series-compensated 400 kV or 500 kV AC line can be achieved with voltage-sourced converters in bipolar configuration without reactive power effects.

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