ENGINEERING CONSULTING SERVICES

Technical Note – Technical Challenges & Risks of HVDC Transmission for Ventilus and Loop of Hainaut Corridors

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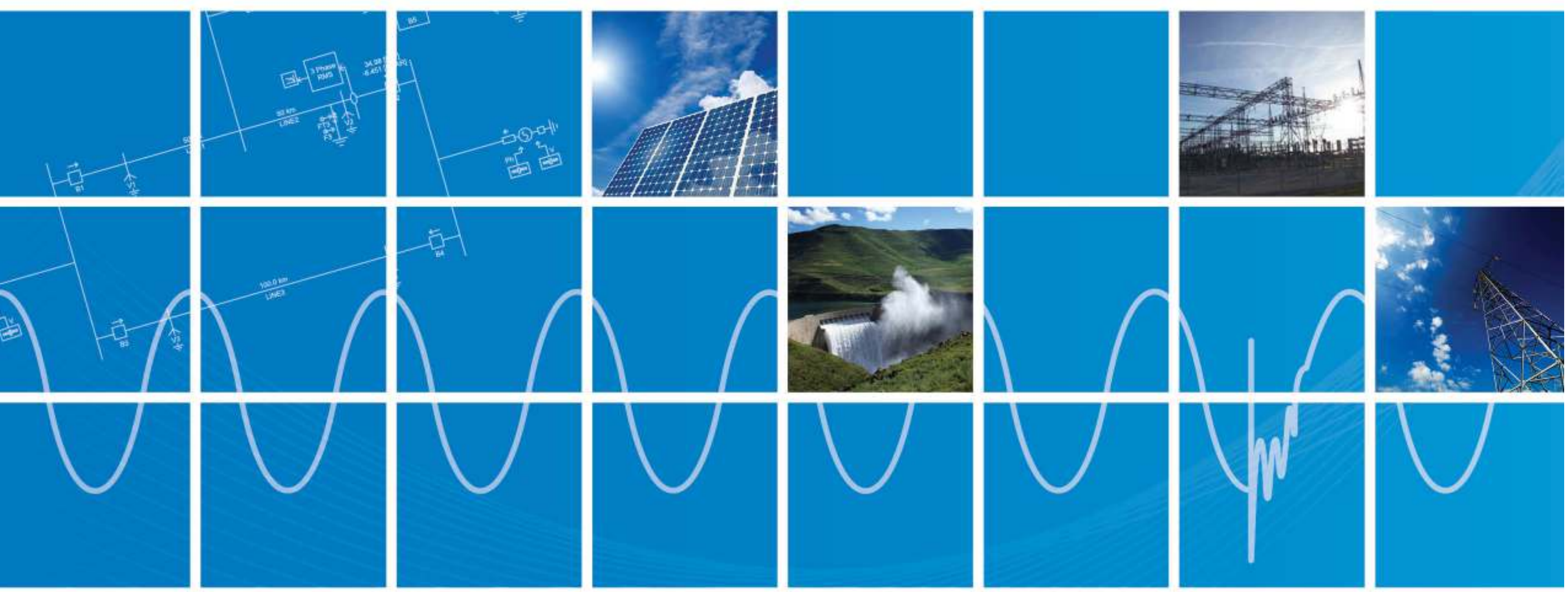
Date: March 04, 2020



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DOCUMENT TRACKING

Rev.	Description	Date
0	First issue	September 23, 2019
1	Second issue	October 06, 2019
2	Third issue	November 02, 2019
3	Fourth issue	December 06, 2019
4	Final issue	March 04, 2020

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1 *Introduction*

The Federal Development Plan of the Belgian transmission network (110 kV – 380 kV) for 2020 – 2030 is structured around three 380 kV network developments: the reinforcement and extension of the internal 380 kV backbone, the development of the offshore network, and the reinforcement and extension of the capacity of interconnections. As a part of the reinforcement and extension of the internal network, ELIA, the Belgian transmission system operator, has performed extensive investigations and proposed development of the Ventilus corridor and the loop of Hainaut as shown in Figure 1 using 380 kV overhead HVAC transmission technology.

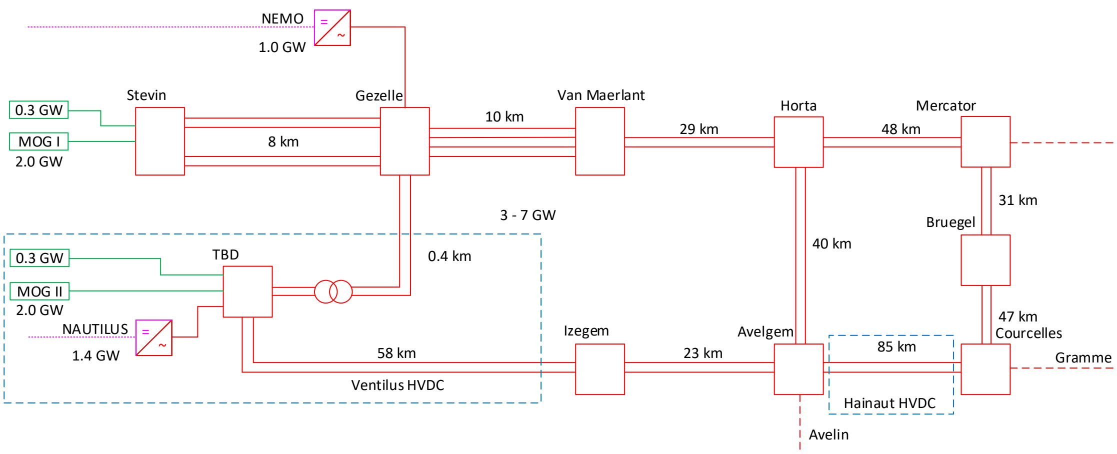

Figure 1: Proposed Ventilus and Hainaut project developments: HVAC Option

However, the public has challenged the conventional overhead HVAC technology based solution and has proposed a HVDC underground cable based solution as shown in Figure 2.

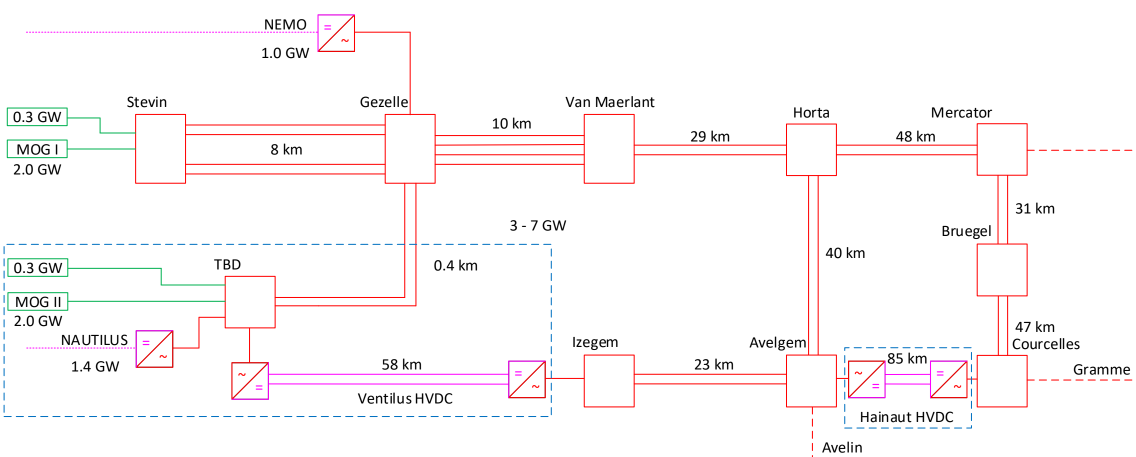

Figure 2: Proposed Ventilus and Hainaut project developments: HVDC Option

In view of this, ELIA has decided to evaluate the technical challenges and risks of considering HVDC transmission and has consulted with Manitoba Hydro International Ltd. (MHI) for technical assistance.

The Ventilus and loop of Hainaut projects have vast technical and economic benefits for the electrical system of Belgium. Both projects will contribute, amongst others, to increase the available transmission capacity and the network security of supply in the northwest region of Belgium.

The available electrical power in the northwest region of Belgium is planned to be increased due to the development of new offshore wind farms (about 2 GW) and the new Nautilus interconnection (1.4 GW). In addition, there is potential onshore wind generation that will be connected to the system. The Ventilus and Hainaut projects will participate heavily to evacuate this power from the western region (a region without large loads) to the rest of the country. The Ventilus project provides an alternative path for the power injected at Stevin (only 380 kV connection to the sea of Belgium), and the Hainaut project eliminates the existing power transfer bottleneck in the Horta-Mercator corridor. Hence, these projects improve the reliability of power transfer in the region and reduces the re-dispatch costs. If the Ventilus and Hainaut projects are implemented using the HVAC option, the projects will assist with improving the system inertia and short circuit strength.

It should be investigated whether the HVDC technology based solution is capable of delivering the expected technical and economic benefit of the Ventilus and Hainaut projects while respecting the following operating requirements specified in the system operation guidelines:

- Ability to recover from normal N-1 contingencies and specific (identified) N-x contingencies.
- Maintain stability for up to the loss of 3000 MW of generation.

In addition, there are technical challenges specific to HVDC technology based projects (such as short circuit strength constraints and dynamic interaction issues with power electronic interfaced devices) which need to be analyzed in detail. Mitigation measures for these challenges are to be identified and the technical requirement for the HVDC solution should be developed once the suitable technical studies are performed. Persisting risks with the HVDC solution should be analyzed and compared with the present state of technology. The following tasks are identified for the evaluation of the HVDC technology-based solution and will be discussed in this report:

- Technical challenges related to the HVDC option and potential mitigation measures
- Technical studies required to be performed to develop a specification
- Discussion of remaining risks associated with the HVDC option
- Comparison of challenges with the existing projects

2 *Technical challenges related to the HVDC option and potential mitigation measures*

This section presents a high-level discussion on identified technical challenges related to the HVDC option and options available to mitigate identified challenges.

1. Challenging network topology

Gezelle-Maerl-Horta and Gezelle-TBD-Izegem-Avelgem 380 kV[1] transmission backbone will transfer a majority of the power generated at offshore windfarms or import power to supply local loads in cases where the wind generation is low (up to 7GW). As such, continuity of power transfer will heavily depend on the availability and reliability of this 380 kV backbone. In particular, 29 km long Maerl-Horta line section and 23 km long Izegem-Avelgem line sections demand special[2] attention. In these overhead lines, 380 kV dual circuits share the same tower structure. Thus, a tower failure or similar catastrophe (i.e. lightning on the tower structure) may result in the loss of the entire line section.

The transmission system's ability to recover during a catastrophic failure of Maerl-Horta line section and Izegem-Avelgem line section will be a key aspect of selecting transmission technology. This network topology will be a challenge for both HVAC and HVDC options. However, there are specific challenges for HVDC technology as discussed below.

Outage (or tripping) of any one of the HVAC transmission lines between Horta and Stevin stations (in particular, the line section between Maerl and Horta) will expose the offshore windfarms and HVDC links to being connected to a transmission network with an almost radial HVDC line. The offshore windfarms and the HVDC links will now be connected to the rest of the Belgian system through the new HVDC link. This will form a unique situation not encountered in transmission systems worldwide. The closest to this condition are the offshore windfarms that are connected to the grid through voltage source inverter (VSC) based HVDC technology. The Elia situation is different in the following ways:

- During the normal operation, the Ventilus HVDC system and 380 kV HVAC connection (Gezelle-Maerl-Horta) will be connected to multiple offshore wind farms as well as NAUTILUS and NEMO HVDC links to the rest of ELIA network. The strength of the HVAC connection may reduce if there is N-1 outage in Gezelle-Maerl-Horta line sections.

- During operation without HVAC (Gezelle-Maerl-Horta) connection, multiple offshore windfarms as well as HVDC links will become an asynchronous island that is connected to the rest of the ELIA network only through Ventilus HVDC system.

This unique situation will require a novel design. Based on MHI's past experience on designing large scale HVDC links for offshore wind transmission, the equipment vendor will have to overcome significant technical design challenges to make the system feasible and meet grid operational requirements. Some of the technical challenges foreseen are listed below.

[1] Izegem-Avelgem transmission line section may be developed as a 380 kV overhead line in HVAC option and as an underground cable in HVDC option.
[2] Other line sections have N-2 compliance for tower failures.

- In this case, grid forming control is likely to be necessary in the new HVDC converter station that will be connected to the potential 'island' of power electronic-based sources described above (Likely 2x3 GW TBD terminal of Ventilus HVDC system). Grid forming technology may be a solution in this case, but this control strategy is a relatively new and mostly untested concept at transmission system levels and this can be considered a risk.

    - To date, the known application of grid forming schemes in HVDC is primarily limited to offshore HVDC converters that transfer offshore wind power to the shore, or for black start operation. In those cases, switching the control mode between grid forming and grid following is not required.
    - The risk associated with the solution described above cannot be easily quantified, due to the lack of operational experience with such systems. Design studies will be required to identify the risks in detail.

  Some potential issues associated with this option are also listed in section 4.

- Control schemes that can switch between grid following and grid forming operations or grid forming control scheme which can share grid forming function with HVAC connection. Such concepts once again are new and untested at transmission level.

- The grid forming converter controls must include current limiting functions in order to maintain the valve currents below the semiconductor current capability. This applies to the fault currents and the currents upon recovery from a fault.

    - During fault events, current limiting is achieved by reducing the converter voltage on the affected phase(s). Upon fault clearance, this current limiting function may impact the recovery of other converter systems synchronized with this converter station. If such events cause uncontrolled flow of active power to the DC side in this (or any other) HVDC link, DC over-voltage trip may take the link out of service. (Even a DC chopper may need to be considered in this link.)
    - The grid forming converter will regulate the voltage and frequency in the 'islanded' area. The remote converter (likely 2x3 GW IZGEM terminal of Ventilus HVDC system) will have to maintain the DC voltage.
    - In case of an AC fault at the DC voltage controller terminal, the power injected to the DC link from the island will lead to a rise in the DC link. Therefore, a DC chopper may be required to dynamically absorb the excess power.

2. Extensive dynamic performance studies

Extensive dynamic performance studies must be performed by the selected vendor to ensure all such scenarios are identified and the necessary actions are envisioned in the controls. This requires that the as-built models from all neighboring power-electronic converters be included in the simulations. Since multiple vendors are involved in this interaction study, sharing the models with the vendor will be a major challenge due to intellectual property protection issues, and will have to be addressed well ahead of starting the studies, otherwise the project design and implementation scheduling will be adversely affected. Model availability is a concern for any new development including the full AC corridor option.

However, the risks are higher when untested schemes, such as the HVDC option discussed here, are in question.

Low short circuit levels negatively impact dynamic performance during fault/disturbance recovery as well as suppressing control (and torsional when applicable) interactions between dynamic devices. Studies have indicated that the converter point of connections may have short circuit ratios that fall below 2.0 (even 1.5 in some cases as per the description in the RFP) in the Stevin loop area. This is a concern, as the low SCR is an indication of potential dynamic response issues with power electronic interfaced devices. The HVDC option will further deteriorate the short circuit ratio condition. This will most likely impact the existing offshore wind farms whose design control settings may not be suitable for operation under low short circuit conditions. Further discussion is provided in section 4.

The expected short circuit ratios for HVAC and HVDC options are shown in Table 1 and Table 2, respectively. It is evident that the Multi Infeed Effective Short Circuit Ratio (MIESCR)[1] [1], [2] will drop significantly with the HVDC option.

Note: While there is no universally accepted standard it is our experience, based on extensive past projects dealing with integration of power electronic interfaced equipment such as renewable generation, that when the short circuit ratios drop below 2, integration of such devices becomes challenging. It should also be noted that power electronic based equipment (existing) implemented with higher MIESCR as the design criteria may show unstable behavior even at MIESCR levels above 2.

Table 1: Expected short circuit levels – HVAC option

HVAC Case	Considering Converter Contributions				Without Converter Contributions			
	N-0		N-1		N-0		N-1	
	Sk" (GVA)	MIESCR	Sk" (GVA)	MIESCR	Sk" (GVA)	MIESCR	Sk" (GVA)	MIESCR
Gezelle (NEMO)	17.66	3.0	17.65	3.0	15.64	2.6	15.51	2.6
TBD (Nautilus)	15.99	4.3	14.61	3.9	14.00	3.7	12.64	3.4

Table 2: Expected short circuit levels – HVDC option

HVAC Case	Considering Converter Contributions				Without Converter Contributions			
	N-0		N-1		N-0		N-1	
	Sk" (GVA)	MIESCR	Sk" (GVA)	MIESCR	Sk" (GVA)	MIESCR	Sk" (GVA)	MIESCR
Gezelle (NEMO)	22.80	1.4	22.78	1.4	12.77	0.7	12.60	0.7
TBD (Nautilus)	22.75	1.4	22.68	1.5	12.72	0.7	12.67	0.7
Izegem	23.06	2.3	18.72	2.1	13.46	1.3	10.67	1.1
Avelgem	32.74	2.6	27.59	2.2	19.10	1.4	13.98	1.1
Courcelles	22.40	3.1	20.40	2.9	15.74	2.1	13.95	1.9

Note: MIESCR is calculated by using short circuit levels at converter terminals, converter ratings and Multi Infeed Interaction Factor (MIIF) between converters. MIIF is typically calculated using RMS dynamic

[1] Since there are more than one converter terminals in the study area, Multi Infeed Effective Short Circuit Ratio (MIESCR), which considers the interaction between HVDC terminals at close proximity, was used to calculate short circuit levels at the converter terminals. Note that MIESCR is a measure derived for LCC based converters, however, it is being used in the industry as screening level indicator for VSC based converters as well.

simulations. Since detailed RMS dynamic models are unavailable, MIIF was approximated using steady state power flow calculations.

System strengthening with addition of synchronous condensers may be required to meet operational requirements of the overall system with high renewable infeed. However, when the connection to the AC grid is lost and the HVDC converter and the remaining inverters form an island, the effectiveness of synchronous condensers is not clear and detailed studies will be required for this assessment. This is discussed in section 4.

3. Interaction of AC/DC systems

HVDC controllers could cause interaction and coordination issues among other power electronics controllers (different suppliers and/or different industrial applications). This phenomenon is more of a challenge when the common point of connection or the general area of the system with multiple power electronic inverters is weak from a short circuit level perspective. Thus, the HVDC option is likely to introduce challenging interaction issues[1].

4. Co-ordination of multiple HVDC systems

Multiple HVDC links in series and/or parallel could trigger the need of a complex “Master Controller” to co-ordinate HVDC systems. Fast supervisory level controls may be required to maintain operational requirements if the HVDC scheme is adopted. Detailed design studies will be required to determine the protection and controls functions that will ensure successful and coordinated operation. Cooperation and coordination among different vendors is required to establish the overall protection and control schemes. The need for a master controller can only be determined after detailed studies.

5. Requirement of complex Remedial Action Schemes (RAS)

Remedial Action Schemes will play a vital role when recovering from system critical disturbances regardless of whether the HVAC or HVDC options is selected. HVDC option, which has parallel and serial connected HVDC schemes with various levels of transient/ temporary overload capabilities, may require complex RAS. As a result, RAS required for HVDC option may be more complicated than the RAS required for HVAC option.

[1] Please see section 4 for more details.

3 Technical studies required to be performed to develop a specification

System studies will be a critical requirement to design the system to operate reliably under the HVDC option. In particular, controlling techniques of individual HVDC systems and their coordination during steady state operation and disturbance recovery should be studied in detail and solutions should be established for various expected operating conditions. The following is a list of the minimum required studies.

- Steady state studies (contingency analysis, PV/QV analysis, and fault analysis)

Steady state studies are required to analyze various expected pre- and post-disturbance operating conditions and identify a set of conditions which may pose challenges in steady state operation as well as transient recovery. In addition, steady state studies will determine solutions for the steady state challenges and limitations.

- Transient stability studies

Transient stability studies using a RMS software tool are vital to evaluate the system's ability to maintain stability subjected to critical disturbances and identify critical operating conditions which may be further studied during the dynamic performance studies. Given the low short circuit levels expected in the study area, suitable "user-defined" HVDC models accurate for the electro-mechanical frequency range (0.1 Hz to 10 Hz) may be required to be developed.

- Dynamic performance studies (DPS)

Dynamic performance studies using an EMT (electromagnetic transient) software tool is essential to study the dynamic performance valid for a wide frequency range. Specially, control strategies required for the HVDC systems may be fine-tuned using DPS. Involvement of various vendors for windfarms and HVDC systems may pose a significant challenge when sharing detailed EMT models. This requirement should be well outlined and established at the tendering stage.

- Small signal stability analysis

A large number of power electronics devices connected to weak AC systems (a system with low short circuit levels) may have poorly damped oscillations. These oscillations may require to be analyzed using eigenvalue-based technique to identify small signal stability characteristics (mode shape and participation factor, etc.) so that suitable controllers (PSS, POD and torsional filters) can be designed. In addition to the eigenvalue-based techniques, analysis of time domain simulation outputs obtained from RMS or EMT simulations may be used to analyze the small signal instability and make suitable adjustments in control systems or develop damping controllers. In general, small signal instability may not be required to study at the specification stage and may only be identified in the specification as a study requirement for the vendor.

- Harmonic studies

High level harmonic studies may be performed at the specification development stage to identify any significant issues that may be specified in the specification so that the vendor is required to find mitigations.

4 Discussion of remaining risks associated with the HVDC option

In addition to the risks introduced previously and those identified by studies, it is expected that the remaining risks will be predominantly related to the possibility of multiple power electronic sources operating in an island, in the absence of conventional synchronous machines.

A summary of the potential remaining challenges are listed below:

- Selection of a suitable robust control mode, and implementing a seamless transfer between grid-connected and islanded operation
    - Although this mode is commonly used in offshore windfarms, it is not common in a transmission-level HVDC link. To the best of MHI's knowledge, it has not been applied in a transmission application with so many inverters and no synchronous machines. Therefore, there is no known installed scheme with similar conditions to compare this application with as a benchmark.
    - Modification of the controls in the existing power electronic converters is highly unfeasible. Therefore, the HVDC converter must be designed to handle this unique condition and to ensure that the operation of the existing systems in the island will not be interrupted.
    - Grid forming control schemes (such as power synchronizer loop, etc.) have been proposed for weak grid conditions. They may not be applicable in strong networks, or may require a different set of controller parameters. Therefore, a robust and control mode change (or control parameter change) may require more complex strategies such that the converter can assess the network configuration and automatically adapt to new conditions, thus ensuring stable and acceptable performance.

      Note: In a conventional system where connection to the AC grid is still available, synchronous condensers can be added at, or in the vicinity of, an HVDC station in order to increase the inertia and phase angle stability, when the AC system is weak.

      In this application where one converter is in charge of 'establishing' the AC voltage for the rest of the island, it is not clear if synchronous condensers will improve the stability of the system or whether their inertia may cause unacceptable interactions with the HVDC converter controls in case of a disturbance. This requires detailed EMT studies to verify whether synchronous condensers will enhance or deteriorate the system performance when operating in an island.

- Impact on the existing conventional AC protection system, when operating in an island (e.g. MOG I)
    - In case of islanded operation, the existing AC protection systems that rely on typical AC system fault levels may not be able to detect faults and trip the faulted section. The power-electronic converters are designed to limit their currents to their respective rated levels. The existing AC system relays that use current levels have been adjusted to detect 'high' fault levels and may be unable to perform successfully when an island of multiple inverters is formed. For this condition, it may be necessary to install additional protective relays or methods for such a configuration.

- Adoption of new technology and complex control schemes
    - An HVDC option like the scheme that is depicted in Figure 2 will be one of the first (if not the first) of this nature. While there are existing HVDC schemes that evacuate bulk power from offshore windfarms (ex. Dolwin in Germany), these HVDC schemes are mostly radial feeds from a single generating location (windfarm) to a single transmission location. MHI sees the proposed HVDC (Ventilus and loop of Hainaut) option as different and one that needs much more reliability as this schemes forms a meshed part of the transmission grid, connecting to multiple sources. Adopting new technology, new protection and controls concepts and, potentially, complicated coordination and remedial action schemes (as described in Section 2) will present risks despite the studies and due diligence that will form the basis for design.

5 Comparison of challenges with the existing projects

(A benchmark and delta analysis on comparable (if any) projects or existing assets)

	Technical challenge	Existing project with similar challenge
1	Challenging network topology	Offshore windfarms with VSC transmission: In Germany: the first three offshore windfarms that were connected with VSC technology (three different vendors supplied the design and equipment for the three projects) had technical issues that took months or years to resolve (full details not published) In Australia, operating wind and solar PV under low SCR conditions have given rise to a number of issues. • 2016 South Australia Back system. • Renewable generation curtailment to meet system security. Specifically, fault ride through concerns and low frequency oscillations that could lead to flicker issues were identified. There is an existing 500 kV HVDC link between The Dalls, Oregon and Los Angeles, California with a parallel 500 kV AC tie line. This is a challenging configuration to keep the parallel AC tie line from overloading if the HVDC has a problem and keeping the HVDC stable if the 500 kV AC tie line trips. Manitoba Hydro Nelson River HVDC originally had a deterministic “Master Controller” and it mal-operated nine (9) times in the first year of operation alone, resulting in a complete shut down of the HVDC link. This performance was deemed unacceptable and it was replaced with some RAS - distinct protection, frequency control, AC damping (Power Oscillation Damping – POD), under-frequency load shedding, cross tripping and runback schemes which has worked very well in over 35 years. Almost all new HVDC links use RAS instead of the Master Controller. There is still one Master Controller called the Generator Master Power Controller (GMPC) in Mozambique, Africa on the Cahora Bassa HVDC system and it has mal-operated a number of times in the last 10 years as not all operating configurations can be programmed until they are experienced.

2	Low short circuit levels	Manitoba Hydro example: The technical solution includes the operation of about 2 GVA of synchronous condensers to support the HVDC operation. There is an existing HVDC link between Delta, Utah and Adelanto, California called the Intermountain Power Project (IPP) built in 1981 +/- 400 kV 1600 MW. It is being refurbished an upgraded to 2400 MW. The Thermal Generating Plant is being shut down and replaced with wind. However, the electrical inertia will need to be replaced with synchronous condenser or converting the thermal generators to synchronous condensers. So far, it appears to be much lower cost to convert the thermal generators as they are still in relatively good condition.
3	Interaction of AC/DC systems	Manitoba Hydro has its Norther Collector system for the HVDC link isolated or basically in an island configuration all of the time. The 32 generating units have PSS (power system stabilizers) with the HVDC in frequency control. There is virtually no load to provide any system damping. There are self excitation issues between the AC filter and the generators at low loading, a 13 harmonic resonance issue and high transient over voltage concerns. These are mitigated via RAS schemes such as tripping the AC filters before completely blocking the HVDC link plus only operating in acceptable operating configuration's. Almost all large HVDC and HVAC systems will have some sort of RAS to successfully integrate them into an existing AC system
4	Co-ordination of multiple HVDC systems	The HVDC link between Quebec, Canada and Boston MA, USA was originally planned as a five terminal system. Only three terminals were built between Radisson, Nicolet (both Canada) and Sandy Pond (USA). During system studies it was found that is almost impossible to operate the 5 terminals because of commutation failures (Note: VSC technology does not have commutation failure issues. It is a specific problem for conventional line commutated (LCC) HVDC technology). There is reportedly a five terminal VSC link in-service in China but so far no information on its operating performance is available.
5	Requirement of complex Remedial Action Schemes (RAS)	Manitoba Hydro Nelson River HVDC originally had a deterministic "Master Controller" and it mal-operate nine (9) times in the first year of operation

		alone resulting the complete shut down of the HVDC link. This performance was deemed unacceptable and it was replaced with some RAS - distinct protection schemes, frequency control, AC damping, under-frequency load shedding, cross tripping and runback schemes which has worked very well in over 35 years. Almost all new HVDC links use RAS instead of the Master Controller. In Africa there is a +/- 533 kV, 2 000 MW HVDC link between Mozambique and South Africa and a parallel 400 kV AC line. The Hydro generation plant has one 415 MW generator allocated to the 400 kV AC bus and four 415 MW allocated to the HVDC and connected through a Bus coupler breaker. The HVDC link is operated with RAS AC Damping control when interconnected (bus coupler closed) and Frequency control with the Bus coupler open.

6 Conclusion

MHI considered the HVDC transmission based developments of the Ventilus and Hainaut transmission upgrades. In MHI's opinion, HVDC technology presents technical challenges due to the unique nature of the scheme. An HVDC option like the one being discussed will be one of the first (if not the first) of this nature. Some of the key challenges and the anticipated risks are tabulated below.
Considering the lack in maturity of this solution and high risk profile, this option is not the preferred and recommended option of MHI. MHI advises not to use DC technology for this specific case.

	Technical challenge	**Risk level**	**Remarks (Risk management)**	**Risks compared to AC option**
1	Challenging network topology	High	• New transmission upgrades to eliminate islanding risk (this is outside the scope) • Advanced HVDC controller design (improve islanded performance – ex. grid forming controls with transition to grid following in a seamless manner • Remedial action schemes	• With HVAC, the topology related challenges are less. Grid forming type HVDC controls will not be required.
2	Low short circuit levels	High	• Use of synchronous condensers/STATCOMs prolong the use of existing synchronous generators • Re-tune windfarm design control settings	• With HVAC, the short circuit levels at point of connection of converters will be higher.
3	Interaction of AC/DC systems	Medium	• Use of synchronous condensers to improve short circuit levels • HVDC controller design improvements • PSS, POD and etc.	• Lower risks as the short circuit levels are higher and one less large HVDC in the network.
4	Co-ordination of multiple HVDC systems	Medium	• Implement a complex "Master Controller" to co-ordinate HVDC systems. • Remedial action schemes	• N/A
5	Requirement of complex Remedial Action Schemes (RAS)	Medium to High	• Improved coordination between HVDC and the synchronous condensers/windfarms	• Requirements for such schemes will be less and hence risks are lower.
6	VSC Technology related Challenges	Low to Medium	• Staging of development so that mature technologies are available for later stages. • Involve various vendors in the design process.	• N/A

7 *References*

[1] Cigre Working Group B4.41, Systems with Multiple DC Infeed, December 2008.
[2] ALSTOM, '*HVDC Connecting to the future*', ALSTOM GRID, 2010.

8 Appendix: Multi Infeed Effective Short Circuit Ratio (MIESCR) Calculations

- ESCR (Effective Short Circuit Ratio) is a measure of the system strength of converter buses of a single HVDC scheme. Typically, an ESCR value greater than 2.5 indicates sufficient strength for the Power/ Voltage stability in the AC system associated with the HVDC scheme.

- Similarly, when multiple HVDC schemes share a common AC system, MIESCR values [1], [2] are used as a measure of the system strength of converter buses. This calculation can be used to identify high risk conditions for sub-synchronous control interactions as they more likely to occur when two or more dynamic devices are connected near a location of low system strength.

- Multi Infeed Interaction Factor (MIIF) relates the interaction between AC voltages of any converter buses and is defined as follows;

$$MIIF_{e,n} = \frac{\Delta V_e}{\Delta V_n}$$

$$\Delta V_e: The\ observed\ votlage\ change\ at\ remote\ bus$$

$$\Delta V_n: The\ step\ change\ applied\ at\ the\ inverter\ bus$$

- MIESCR is defined as follows:

$$MIESCR_i = \frac{(SCC_i - Qf_i)}{Pdc_i + \sum_j (MIIF_{j,i} \times Pdc_j)}$$

SCC_i	=	Short circuit MVA at the converter bus
Qf_i	=	Bus filter and capacitor MVA
Pdc_i	=	Rated dc power of the HVDC link connected to bus i
Pdc_j	=	Rated dc power of the link at bus j
$MIIF_{j,i}$	=	MIIF calculated at bus j, for 1% voltage change at bus i

9 Appendix: Embedded HVDC in the AC network – Specific questions from ELIA.

- Could this configuration trigger system stability issues (voltage, frequency) and adverse AC system interactions?
  - Stability issues, more specifically, dynamic response issues may have to be addressed due to weakening of the AC system locations where wind generation is expected to be connected.
  - Challenges include fault recovery, unstable interactions between multiple inverter based devices
  - Difficulty of Voltage control during recovery from system events

- May require complex AC protection coordination schemes
  - Run back schemes may have to be identified to maintain system stability

- Cannot automatically take over load of parallel AC lines
  - Fast run back schemes may be a solution. These solutions are identified though detailed system studies.
  - Furthermore, the existence of parallel AC path(s) with the HVDC link may require a special control strategy in the HVDC scheme in order to prevent power circulation between HVDC and the parallel AC corridor(s). Such techniques are applied in a few in-service HVDC systems

- Multiple HVDC links in series and/or parallel could trigger the need of a "Master Controller"
  - Fast supervisory level controls may be required to maintain operational requirements if the HVDC scheme is adopted. Detailed design studies will be required to determine the protection and controls functions that will ensure successful and coordinated operation. Cooperation and coordination among different vendors is required to establish the overall protection and control schemes.

- HVDC controllers could cause interaction and coordination issues among other Power Electronics Controllers (different suppliers and/or different industrial applications)
  - This phenomenon is more of a challenge when the common point of connection or the general area of the system with multiple power electronic inverters is weak from a short circuit level perspective. Thus, the HVDC option is likely to introduce challenging interaction issues.

- VSC in weak ac systems
  - Small signal instability concerns
    - This is not likely a critical challenge if a coordinated design approach can be adopted with all equipment vendors cooperating to provide model data and cooperating to make necessary adjustments to control settings and designs of their equipment.
  - Unexpected trips of the HVDC links when operating under Low SCR conditions
    - Risk can be minimized through proper design and detailed verification studies
  - Unacceptable response of the AC system due to low SCR conditions
    - Risk can be minimized through proper design and detailed verification studies