

6 HVdc Converter Stations and Electrodes

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6.1 Introduction

The Labrador-Island Link HVdc system is configured as a ± 320 kV 900 MW Line Commutated Converter HVdc bipolar transmission system with two sections of overhead transmission line, the Strait of Belle Isle marine crossing, shore line pond return electrodes, and converter stations at Muskrat Falls and Soldiers Pond. The total transmission line length is approximately 1100 km depending on final route selection.

The overall HVdc system configuration, as partially depicted in

Figure 9, is described in the “Overview of Decision Gate 2 Capital Cost and Schedule Estimates”, Figure 2¹³⁴. The Strait of Belle Isle (SOBI) cable marine crossing is comprised of 3 ± 350 kV submarine cables that enter the Strait via horizontal directionally drilled (HDD) holes from both shores, and then laid on the sea floor with appropriate cable protection. The cable route is approximately 30 km long.

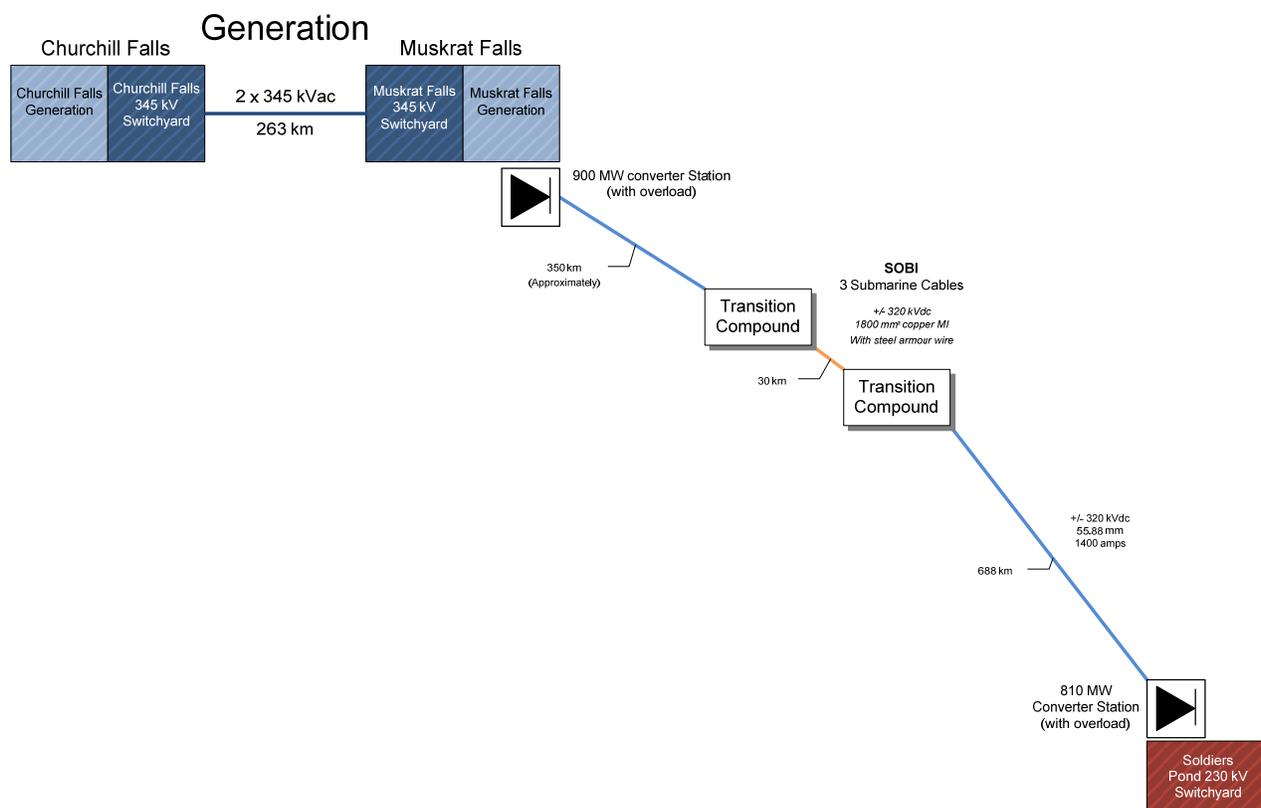


Figure 9: Labrador-Island Link HVdc System Configuration

¹³⁴ Exhibit CE-51 Rev.1 (Public), Nalcor, “Technical Note: Muskrat Falls Generation Facility and Labrador – Island Transmission Link Overview of Decision Gate 2 Capital Cost and Schedule Estimates”, August 2011

6.2 Review Considerations

Most of the documentation available was for a 1600 MW 3-terminal HVdc system to Soldiers Pond and Salisbury, New Brunswick. With the decision at DG2 to advance the Infeed Option, little documentation on the new proposed configuration was available. This lack of information on the new project definition hampered MHI's review.

MHI examined available documents to assess the suitability of the specified technical design parameters to meet the objectives of the overall project, cost estimate, and schedule. This report includes a discussion on technical specifics, and provides a basic understanding of the technology and MHI's findings.

The Labrador-Island Link HVdc system is an integral part of the Infeed Option to supply the Island of Newfoundland with a reliable dedicated source of energy. This requires significant attention to the project definition and design requirements of the HVdc system to be designed and built by the manufacturer.

One of the primary requirements identified in the design progression is for the HVdc system to operate with an overload capability that would cover the loss of one pole, or one-half of the HVdc transmission capability.¹³⁵ Prior studies using a simplified energy balance model of the Island system showed that, with a dc capability per pole of 2.0 pu power transfer for 10 minutes followed by a continuous 1.5 pu of pole overload capability the risk of load shedding due to loss of a single pole would be reduced¹³⁶.

The Labrador-Island Link HVdc system is designed for an N-1 contingency (loss of any one element) and the analysis considers this, together with relevant industry standards.

Nalcor has noted, as their first assumption in section 6.3 of Exhibit 30 General Overview of Design Assumptions, that only proven technologies will be considered, unless it can be clearly demonstrated that emerging technologies can be as reliable and provide significant cost or schedule improvements.

Nalcor states that the designs will be consistent with:

- Good Utility Practices
- Life Cycle Costing
- Nalcor Health and Safety Policies
- Nalcor Environmental Policy and guiding principles
- Nalcor asset management philosophy
- Applicable Standards, Codes, Acts and Regulations

¹³⁵ Exhibit 30, Nalcor, "Technical Note: Lower Churchill Project Design Progression, 1998 to 2011", July 2011

¹³⁶ Exhibit CE-31 Rev.1 (Public), Teshmont, "Gull Island to Soldiers Pond HVDC Interconnection – DC System Studies – Volume 1", December 1998

The Muskrat Falls Generating Station is rated at 824 MW (515 MW continuous rating) and produces an average of approximately 4.91 TWh annually.¹³⁷ Connected to the Muskrat Falls converter station switchyard would be two 263 km, 345 kV transmission lines to Churchill Falls where an additional 300 MW of recall is available for NLH use. Part of this recall is currently allocated for Labrador loads.¹³⁸

Prior to DG2, considerable studies were conducted for the Gull Island development based on the concept of a three terminal 1,600 MW, HVdc system. After DG2, the HVdc system was redefined with Muskrat Falls Generating Station to be constructed first and a power transfer of 900 MW on a conventional LCC two terminal point to point HVdc transmission system.

The assessment of the Labrador-Island Link HVdc Converter Stations was based on information and documentation provided by Nalcor and meetings with Nalcor staff. The cost estimates were benchmarked against industry standards and costs and estimates related to other projects from MHI's experience.

6.3 Documents Reviewed

The following documents were reviewed:

6.3.1 Teshmont Consultants, 1998, Gull Island to Soldiers Pond HVdc Interconnection – Engineering Review and Update of Capital Cost Estimate¹³⁹

The conclusion of Teshmont's engineering review is that, with current proven technology, transmission of 800 MW from the Gull Island generating plant to Soldiers Pond is feasible and will improve the reliability of the supply of electricity to customers on the Island of Newfoundland.

The Teshmont review of cost estimates indicates that the system could be built for a capital cost based on 1998 Canadian dollars of \$1,428 million within an accuracy of $\pm 10\%$.

A summary of changes stated in the Teshmont engineering review included:

- *"The valve groups will be designed for continuous and short time overload capability so that load shedding will not occur in the Newfoundland ac system for transient and permanent pole outages on the Interconnection.*
- *The dc converters will have a single valve group per pole rather than two groups per pole. This will reduce costs and provide a more reliable system as compared to systems considered in previous studies.*
- *The dc line will be constructed with an overhead ground wire. The overhead ground wire will greatly reduce the number of transient pole faults from lightning strikes.*

¹³⁷ Exhibit CE-27 Rev.1 (Public), Nalcor, "Muskrat Falls Hydroelectric Development Summary of Studies on Firm and Average Energy Production", June 2011

¹³⁸ Response to RFI PUB-Nalcor-32

¹³⁹ Exhibit 18, Teshmont Consultants, "Gull Island to Soldiers Pond HVdc Interconnection – Engineering Review and Update of Capital Cost Estimate", June 1998

- *The submarine cable crossing of the Strait of Belle Isle will consist of three submarine cables, each rated for 1500 A. This rating allows continuous operation of up to 50% overload on each pole with a single cable. One cable is provided as a spare.”*

6.3.2 Hatch 2008, Volumes 1 to 6 HVdc Integration Study

The Hatch 2008 Study is available in six volumes and is found in Exhibits: CE-03 (Public), CE-04 Rev.1 (Public) through CE-07 Rev.1 (Public), and CE-08 Revision 1 (Public). The Scope of work in this study included: power flow and short circuit analysis, comparison of the performance of conventional and Capacitor Commutated Converter (CCC) HVdc technologies, transient stability analysis, cursory evaluation of alternate HVdc configurations, and development of a multi-terminal HVdc model for future system studies.

The principal objectives of the HVdc System Integration Study were to:

- *“Demonstrate the feasibility of a multi-terminal HVdc link connecting Labrador, Newfoundland, and New Brunswick given the requirements of the Newfoundland system.*
- *Determine the system additions required for integrating the proposed three-terminal HVdc system into the Labrador and Newfoundland systems. Although basic consideration was given to integration into the New Brunswick system, the study concentrated on the Labrador and Newfoundland systems. A separate system impact study was to be performed by the New Brunswick system operator to assess the requirements in New Brunswick.*
- *Determine the limitations of the proposed HVdc system.*
- *Determine feasible mitigation steps to ensure that the integrated system performs in an acceptable manner.*
- *Ensure that the integrated system design minimizes the need for load shedding in Newfoundland.”¹⁴⁰*

Many of the issues observed are not necessarily due to the HVdc infeed but rather the lack of transmission linking the generation in the west to the load in the east. The study also recommended that a minimum ESCR of 2.5 for the inverter ac systems be maintained. The feasibility of the proposed multi-terminal HVdc system was demonstrated with good performance and a number of key ac system upgrades were identified to support the HVdc inverter connection¹⁴¹.

It must be noted that these studies were not related to the Muskrat Falls and Labrador-Island Link HVdc projects that make up the Infeed Option.

6.3.3 Hatch 2008, Voltage and Conductor Optimization¹⁴²

Two transmission scenarios were evaluated in the Hatch study to determine if there would be any impact on the selection of voltage and conductors. The two scenarios are as follows:

¹⁴⁰ Exhibit CE-03 (Public), Hatch, “The Lower Churchill Project DC1020 - HVdc System Integration Study Volume 1 - Summary Report”, May 2008

¹⁴¹ Exhibit CE-03 (Public), Hatch, “The Lower Churchill Project DC1020 - HVdc System Integration Study Volume 1 - Summary Report”, May 2008

¹⁴² Exhibit CE-01 Rev.1 (Public), Hatch, “The Lower Churchill Project DC1010 - Voltage and Conductor Optimization “, April 2008

- Scenario 1: 800 MW transmission from Gull Island to Soldiers Pond
- Scenario 2: 1,600 MW transmission from Gull Island with 800 MW to Soldiers Pond and 800 MW to Salisbury, N.B.

A single conductor is recommended for ice buildup mitigation

- Scenario 1: ± 400 kVdc with a single, 50.4 mm diameter conductor.
- Scenario 2: ± 450 kVdc with a single, 58.0 mm diameter conductor.

The Hatch 2008 study determined that there was little difference in cost between the two scenarios.

6.3.4 Siemens 2010, HVDC PLUS Feasibility Study¹⁴³

This confidential report, which discusses the option of transmitting power from the Lower Churchill Falls Project (LCP) with the new multilevel voltage source converter (VSC) technology, was reviewed by MHI.

6.3.5 ABB 2011, Lower Churchill Project, PSS/E Transient Stability Pre-study¹⁴⁴

This confidential report which was related to the application of VSC technology was reviewed by MHI.

6.3.6 Nalcor's Lower Churchill Project Design Progression 1998 -2011¹⁴⁵

The original configuration of the Labrador-Island HVdc Link was based on a bipole system proposed in 1998 with an 800 MW transmission system from Gull Island to Soldiers Pond having a pole overload capacity of 200% (800 MW) for 10-minutes and 150% (600 MW) continuous.

With the decision at DG2 in November 2010, the 1600 MW multi-terminal HVdc scheme, as studied in 2008, was replaced with a smaller point-to-point system from Muskrat Falls to Soldiers Pond (Infeed Option). It was determined that the HVdc link should be sized at 900 MW, based on the size of the Muskrat Falls development, obtaining up to 300 MW of recall from Churchill Falls and moving an estimated 4.9 TWh over the HVdc scheme. Analysis carried out in June and July of 2010 confirmed that a 900 MW HVdc link between Labrador and the Island would require a minimum operating voltage of ± 320 kV to ensure that transmission losses for the proposed HVdc system would be in the order of 10% at peak.

While this is a bipole HVdc system, it still requires a return path to operate under normal conditions and provide a return path during infrequent periods of mono-polar operation. Earlier studies, in particular a 1998 report by Teshmont, assumed that a sea electrode would be installed in Lake Melville for the Labrador converter station and in Conception Bay South for the Soldiers Pond converter station.

¹⁴³ Exhibit CE-62, Siemens, "HVDC PLUS Feasibility Study" June 2010

¹⁴⁴ Exhibit CE-63, ABB, "Nalcor Energy - Lower Churchill Project, PSS/E Transient Stability Pre-study", July 2011

¹⁴⁵ Exhibit 30, Nalcor, "Technical Note: Lower Churchill Project Design Progression 1998 to 2011", July 2009

In 2007/2008 Nalcor initiated an electrode review by Statnett of Norway¹⁴⁶. The resulting report recommended sea electrodes for both converter stations and did not consider other types of electrodes, such as land, shoreline or shoreline pond electrodes.

Accordingly, in 2009, Nalcor assembled a panel of five experts to complete a thorough electrode review. The panel, working closely with Hatch, issued the report on electrode types and locations¹⁴⁷ in 2010. This report recommended the use of shoreline pond electrodes for the Soldiers Pond converter station and recommended further work to confirm type and location of electrodes for the Labrador converter station. This further work was completed and culminated in the report "Electrode Review, Confirmation of Type and Site Selection"¹⁴⁸. This report recommended shoreline pond electrodes for the Labrador converter station to be constructed on the Labrador shore of the Strait of Belle Isle and confirmed shoreline pond electrodes for the Soldiers Pond converter station to be constructed on the east shore of Conception Bay.

6.3.7 Hatch 2010, HVdc Sensitivity Studies Final Summary Report¹⁴⁹

The purpose of the Hatch 2010 study was to explore selected topics identified as additional work subsequent to the completion of the HVdc System Integration Study identified in section 6.3.2. Stated goals of the study included:

- *"HVdc Sensitivity Studies - Sensitivity studies to investigate whether system reconfiguration, relaxation of the planning criteria, special protection schemes, or some combination thereof would enable the removal of the Pipers Hole synchronous condensers, while facilitating acceptable system performance.*
- *PSSE Model Modification - Modification of the multi-terminal PSSE model, developed as part of the original HVdc System Integration Study, reflects a potential alternate cable route through Cabot Strait and overhead line in the Maritime Provinces.*
- *VSC Risk Assessment - A high-level risk assessment of VSC technology for both a multi-terminal hybrid HVdc scheme and a Labrador to Island point-to-point HVdc scheme.*
- *Ac/dc Line Proximity Issues - A high-level identification of potential interaction issues resulting from the location of ac and dc lines in close proximity.*
- *Bipole Block Impacts - Investigation of the impact of a bipole block on the Island ac system."*

The study stated that "the main issue in the Island system with the HVdc infeed is the lack of inertia and resulting frequency decay due to faults which cause the HVdc infeed to fail commutation; the nearer the fault location to Bay d'Espoir generating station, the more power is temporarily lost and the more severe the system frequency decay." The study concluded that the power system performance

¹⁴⁶ Exhibit CE-09 Rev.1 (Public), Hatch, "Lower Churchill Project DC110 - Electrode Review Gull Island and Soldiers Pond", March 2008

¹⁴⁷ Exhibit CE-11 (Public), Hatch, "Lower Churchill Project DC1250 - Electrode Review Types and Locations", March 2008

¹⁴⁸ Exhibit CE-12 Rev.1 (Public), Hatch, "DC1500 - Electrode Review, Confirmation of Type and Location Final Report", December 2010

¹⁴⁹ Exhibit CE-10 Rev.1 (Public), Hatch, "Lower Churchill Project – DC1210 – HVdc Sensitivity Studies", July 2010

of the 800 MW bipolar case was worse than the 600 MW monopolar case. A significant improvement in system performance was obtained with the addition of 2 – 300 MVAR high inertia synchronous condensers. A third synchronous condenser was suggested for reliability.

The report states that “without the installation of synchronous condensers at Pipers Hole, the Sunnyside bus requires dynamic voltage support in the form of a Static Var Compensator (SVC)”. Either a SVC at Sunnyside or a new 230 kV circuit between Bay d’Espoir and Western Avalon will provide an acceptable system performance for all contingencies except the three-phase fault at Bay d’Espoir.

The Hatch 2010 study stated that:

“with the Soldiers Pond infeed modeling VSC technology, all simulations were stable and the post-fault voltages were within acceptable limits for all of the contingencies described in Table 4.1 without any synchronous condensers operating at Soldiers Pond and without any new synchronous condensers elsewhere in the Island system (with the exception of the Holyrood machines running as synchronous condensers).”

With regards to the ac/dc proximity issues, the study states that:

“Based on the available literature and current industry experience, the use of a hybrid line with the HVdc and ac conductors on a common tower may not be suitable for the proposed line route, mainly due to the high level of interaction between the ac and dc lines and the potential for HVdc to ac conductor faults. In situations where common towers are used for short distances, the risk of an HVdc to ac conductor fault may be acceptable.”

The use of HVdc and ac lines in close proximity on separate towers may be suitable if an acceptable separation can be maintained. The suitability of this option would require detailed studies in order to determine potential candidate line configurations, and any required mitigation measures to ensure acceptable performance of the integrated HVdc and ac systems. Current industry experience can be used as a starting point for determining a potential minimum separation distance between the HVdc and ac lines. Once this is identified the suitability of the existing right of way can be better assessed.

The use of a direct buried ac cable, with the HVdc on towers on the same right of way may be suitable; however, studies would be required to determine the potential effects of HVdc ground faults on the buried ac cable.

6.3.8 NLH, 2010, Preliminary Transmission System Analysis, Muskrat Falls to Churchill Falls Transmission Voltage¹⁵⁰

The report states the following in the executive summary:

“Preliminary analysis indicates that at least four single conductor per circuit 230 kV transmission lines would be required between Muskrat Falls and Churchill Falls for stable operation of the power system during expected contingencies. Moving to a two conductor

¹⁵⁰ Exhibit 59, NLH, “Preliminary Transmission System Analysis, Muskrat Falls to Churchill Falls Transmission Voltage”, November 2010

bundle at 230 kV results in a minimum of three 230 kV transmission lines between Muskrat Falls and Churchill Falls to provide reasonable assurances of stable system operation.

Alternatively, moving to the 362 kV transmission class indicated that a minimum of two 315 kV or two 345 kV transmission lines can be expected to provide reasonable system performance. There are advantages and disadvantages of each the 315 kV and 345 kV operating voltage.

For project costing, it is recommended that two 345 kV transmission lines, with a two conductor bundle of 795 MCM 26/7 ACSR "Drake" per phase be assumed. In addition, to ensure acceptable voltage control on line open end conditions, four 345 kV, 45 MVAR shunt reactors (one per each transmission line end) be included.

Detailed stability studies in final design will be required to determine the technical applicability of moving to a 315 kV operating voltage level.

Further analysis is required to determine if application of on-load tap changers, on the 735/345 kV autotransformers, can be sized to provide the necessary voltage control and eliminate the need for independent shunt reactors. This will ultimately be a decision of economics and operability in final project design."

6.4 HVdc Technology Overview

HVdc transmission is a proven, mature technology that has been in commercial service with many utilities since the 1950's, with numerous projects implemented worldwide. The first viable HVdc transmission technology is termed Line Commutated Converter (LCC) technology, which is a directional current flow dc configuration. LCC HVdc uses a power electronic thyristor switching device as the main engine of the LCC system to switch the current on at the correct instant thereby converting ac into dc at one end of the system (Muskrat Falls), and dc current back into ac at the receiving end (Soldiers Pond).

During the 1990's a second type of HVdc technology became commercially viable based on the voltage sourced converter (VSC) concept. The switching device in VSC HVdc system is an insulated gate bipolar transistor which can be switched numerous times in each fundamental frequency time period. The amount of power transferred is controlled by switching the voltage applied to the dc side of the circuit. There are fundamental differences between LCC and VSC transmission systems. One significant difference is that VSC technology can control both real and reactive power injected into the system at the inverter end. Unlike LCC implementations, VSC technology does not require a minimum Equivalent Short Circuit Ratio (ESCR) and can be used in a black start situation. Both LCC and VSC technologies are commercially viable and are being specified in projects where power transfer ratings are equivalent (i.e. ± 500 kV 1000 MW systems).

HVdc transmission systems are used for the following reasons:

- Economics for interconnecting ac systems over long distances. The overall capital construction costs and operating costs are lower for HVdc transmission when compared to ac systems covering the same long distance. The additional costs of building HVdc converter stations

make dc systems economical only when compared to a long-distance ac transmission application.

- HVdc transmission lines use two conductors instead of three for ac systems, which result in smaller towers for the amount of power transfer.
- More power can be transmitted using dc than ac in the same sized transmission corridor.
- HVdc can asynchronously connect systems with different frequencies; this is not possible with ac transmission.
- HVdc transmission systems allow power flow on the dc transmission path to be precisely controlled; this degree or range of control is not possible with ac systems
- Fast, flexible dc controls can be used to support operations of ac systems either with reactive support or stabilization during disturbances.

There are a number of configurations used for HVdc applications throughout the world with both LCC and VSC transmission technologies. The two main HVdc LCC configurations in use are monopole and bipole configurations for point to point HVdc transmission. The monopole and bipole configuration can include a neutral conductor, an earth return current path or sea return current path (which includes shore electrodes).

6.4.1 Configurations of HVdc Technology

The following configurations are applicable to both the VSC technology as well as the LCC technology. The main difference is that the valves themselves are configured with new switching devices resulting in different operating characteristics.

Regarding monopole HVdc, one dc pole's polarity will operate with a positive or negative dc voltage. The return path can be a conductor, operating at earth (zero) volts or the earth itself. The connection to the earth can be an earth, shoreline or sea (water) electrodes. Figure 10 shows a monopole earth return system where another variant would be a solid return conductor with one end grounded.

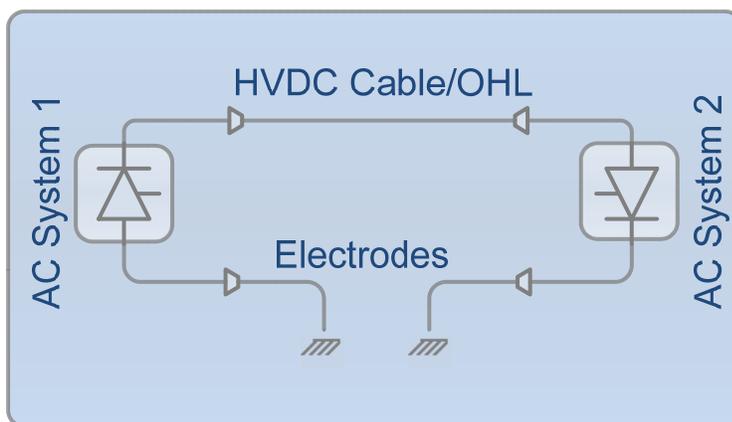


Figure 10: Monopole Configuration with Electrode Return (Source: Alstom)

Bipolar HVdc systems consist of both a positive and a negative pole where the dc current will travel via the positive pole and return via the negative pole. The connection point between the positive and negative poles is grounded to the earth. In the event that one pole faults, the other un-faulted pole can remain in service, using either the electrodes to transfer the current or use the neutral conductor as the return path.

The advantage of a bipolar system is that in normal operation virtually no earth or neutral current is present. When one pole is out of service due to a fault or for scheduled maintenance, 50% of the transferable capability is still available and with overload capability this can even be higher. See Figure 11. The red line shows the current path when one pole is out of service.

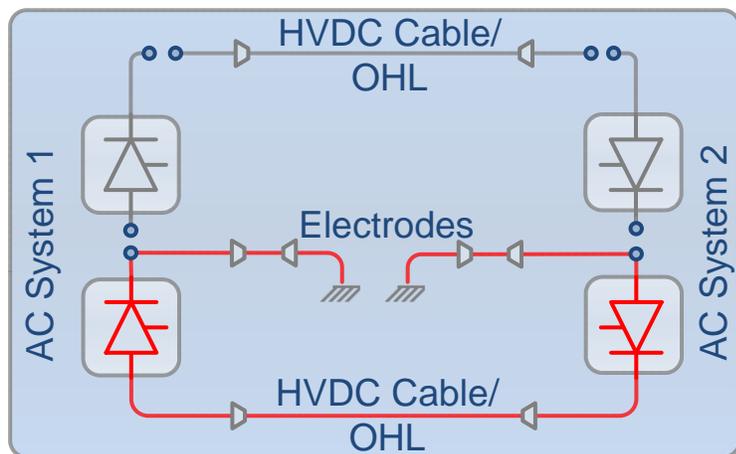


Figure 11: Bipole in Monopole Operation (Source: Alstom)

6.5 Choice of HVdc Technology

A new HVdc valve technology exists with the recent introduction of the multi-module voltage source converter (VSC) valve. VSC systems of this size and length have not been built or operated anywhere in the world to date.

According to documents supplied by Nalcor, a risk assessment indicated that the VSC HVdc technology would not be considered at this time as there was no clear economic or technical advantage thus retiring this risk.¹⁵¹ Voltage Source Converters have a slow clearing time for a dc fault, do not require synchronous condensers to support the dc to ac conversion process, and have acceptable system performance when the ESCR is less than 2.0 pu. ESCR is an important design parameter as it relates to both voltage and frequency control on the island. Nalcor has stated:

“Given expected continued advancement of VSC technology, Nalcor has not ruled out VSC as a technology option in the future.”

¹⁵¹ Exhibit CE-52 Rev.1 (Public), Nalcor, “Technical Note – Strategic Risk Analysis and Mitigation”, August 2011

At DG2, however, with no technical or economic benefits for VSC technology, Nalcor elected to include proven LCC technology in the DG2 Basis of Design and to avoid the VSC risk premium as identified in Confidential Exhibit CE-52.”¹⁵²

There are many technical considerations and requirements, and for VSC technology to be considered, it must provide similar or superior performance and a lower cost.

New technology recently announced by ABB that would improve the performance of a VSC HVdc link is the development of an HVdc breaker. The ABB HVdc breaker claims to operate within 2 milliseconds and would solve the slow dc fault clearing time which is an issue for VSC valves.¹⁵³

6.6 Muskrat Falls Converter Station

The Muskrat Falls converter station is planned as a LCC type of HVdc system. This is a proven technology with a long history of successful application to numerous projects. The converter station design is a 900 MW \pm 320 kV bipolar system.¹⁵⁴ This configuration can operate either mono-polar or use only one pole with the earth return to transmit half of the power except as noted below with respect to overload capability.

Each pole will normally operate at a continuous rating of 450 MW. The overload capability for each pole specified in the design progression is for 200% or 900 MW for ten minutes, and 150% or 675 MW continuous rating. The Infeed Option requires this overload capability to mitigate the loss of a pole contingency. The Infeed Option as defined in the design progression has no other interconnections, and thus cannot rely on power from alternative sources. The most likely event is the loss of a pole, which corresponds to a loss of 450 MW. Without the overload capability, the loss of 450 MW could not be covered by the Soldiers Pond Converter Station. This loss of generation would lead to potential load shedding, or possible system collapse leading to a black-out. The 10 minute overload rating with appropriate controls helps with system stability issues. The 150% overload rating results in a single contingency of 225 MW which is the difference between the 200% rating and the 150% rating of the two poles. This continuous overload capability translates into increased costs of the converter station equipment and, depending on the design, premature aging of the equipment may occur with extended use. A continuous overload rating specifies that the equipment has essentially been designed for a total of 1,350 MW of power transfer for the HVdc system.

A converter station typically has both an ac and a dc switchyard. The ac switchyard for Muskrat Falls is at the 345 kV level with two lines to Churchill Falls. There would be four ac filter banks to adsorb the ac side harmonics and provide some of the reactive power requirements of the HVdc converters. There are only two station service transformers planned to provide auxiliary power at the converter stations; however, a third may be required for converter station reliability.¹⁵⁵ Station service or a similar feed is

¹⁵² Response to RFI MHI-Nalcor-67 Rev.1

¹⁵³ Jürgen Häfner (ABB), Björn Jacobson (ABB), “Proactive Hybrid HVdc Breakers – A key innovation for reliable HVdc grids”, Cigré International Symposium, Bologna, September 2011

¹⁵⁴ Exhibit 30, Nalcor, “Technical Note: Lower Churchill Project Design Progression 1999 to 2011”, July 2011

¹⁵⁵ Exhibit 30, Nalcor, “Technical Note: Lower Churchill Project Design Progression 1999 to 2011”, page 24 Proposed Single Line Diagram, July 2011

required to provide redundancy so full power output from the converter station can be maintained when one station service transformer is out for maintenance or has failed.

The requested single line diagram of the HVdc switchyard and converter station equipment was not available at this time. The single line diagram provided by Nalcor in response to RFI MHI-Nalcor-64 was for the ac switchyard.

Based on MHI's experience, most of the HVdc converter equipment has a design life of 35 to 40 years whereas the life of the project is 50 years. The HVdc controls and protection equipment have a life of only about 15 to 20 years and require replacement at a cost of about \$ 12 million. Converter transformers have an expected lifespan of 35 years, and typically cost approximately \$7 to 9 million. Based on the preliminary design information, there would be seven transformers in total, including a spare at each converter station. These costs are typical and derived from review of tender documents on other projects.

There were no specific performance requirements defined for the converter station available for MHI's review. MHI understands that a functional specification is being prepared by the EPCM contractor to be issued to HVdc suppliers as part of the detailed design. MHI is unable to comment on the adequacy of performance requirements and their conformance with current industry standards.

6.7 Soldiers Pond Converter Station

The Soldiers Pond converter station is similar in design to that of the Muskrat Falls converter station. Each pole will be rated at 450 MW with similar overload capabilities.

A unique feature of the Soldiers Pond converter station is that the ac switchyard contains three 300 MVAR synchronous condensers (Exhibit 30), two of which are required to keep the ESCR above 2.5 per unit to minimize the number and risk of commutation failures. Units which have a high inertial constant of 7.2 s are preferred over conventional machines with a rating of 2.5 s or lower. The synchronous condensers also provide continuously variable reactive power to aid in the dc to ac conversion process and control overvoltages. The synchronous condensers MVAR requirement can be adjusted to follow the daily load cycle requirement for reactive power and thus can minimize the switching operations on the ac filters. The synchronous condensers with a high inertial constant of 7.2 are very expensive devices and require extensive maintenance.

The performance of a LCC HVdc system becomes unacceptable below a 2.5 pu ESCR. There is the potential for numerous commutation failures from nearby electrical faults which may cause outages and equipment failures.

The inertial constant of 7.2 s for the synchronous condensers is required to stabilize the performance of the ac transmission system during disturbances. The added electrical inertia allows the HVdc system to ride through a system fault which could otherwise cause the HVdc system to block, slows frequency decay, and thus reduces the potential need for load shedding.

Again, no detailed information on the HVdc switchyard was made available for MHI's review other than the single line diagram for the Soldiers Pond ac switchyard.

6.8 AC System Upgrades Required for Labrador-Island Link HVdc System

AC system upgrades required for the HVdc system will include the conversion of two existing Holyrood Units # 1 and # 2 to synchronous condenser operation. Holyrood Unit #3 was previously converted to synchronous condenser operation. The replacement of a number of high voltage breakers is required because of the higher short circuit level generated by the additional synchronous condensers. The addition of two 300 MVAR synchronous condensers at the Soldiers Pond Converter Station is required to raise the ESCR above 2.5 pu. A third 300 MVAR synchronous condenser is required for reliability.

6.9 Electrodes

The electrode line is a distribution type line connecting the Muskrat Falls Converter Station to the electrode site location. The electrode provides a ground return path for unbalanced currents during bipolar operation and for the line current during monopolar operation.

The electrode line has been designed with wood pole structures for some 310 km from Muskrat Falls to the SOBI. Nalcor is considering the possibility of placing the electrode line conductors on the main HVdc transmission tower, which could eliminate the cost of the wood pole line. The placing of the electrode line conductors on the main HVdc transmission tower is feasible and has been implemented for shorter distances on other operating systems such as the Cahora Bassa Songo Converter Station.

The original studies done by Teshmont and Statnett had recommended sea electrodes. Nalcor was concerned that other types of electrodes were not considered in these studies. A sea electrode does have issues with chlorine production, compass navigation, and fish habitat concerns. As a result, the electrode will now be a shore line electrode which was recommended by a panel of five experts which would be easier and less expensive to install and maintain.^{156,157} The electrodes are rated for a 40 year life span while the life of the project is 50 years, indicating a gap. There is also the possibility of running continuously for one year in the event that one undersea cable plus a spare cable is not available for any reason.

There is a second electrode line connecting the Soldiers Pond converter station to the electrode site location. The electrode line will have a 50 year reliability level return period. The electrode line from Soldiers Pond is a wood pole structure some 10 km in length to Dowden's Point on the east side of Conception Bay.

¹⁵⁶ Exhibit CE-11 (Public), Hatch, "The Lower Churchill Project DC1250 – Electrode Review, Types and Locations", March 2010

¹⁵⁷ Exhibit CE-12 Rev.1 (Public), Hatch, "DC1500 Electrode Review, Confirmation of Type and Site Selection", December 2010

6.10 Cost Estimate Analysis

MHI reviewed the cost estimates used by Nalcor for the converter stations, electrodes and synchronous condensers using industry accepted benchmarks and information from similar projects.

The two converter stations are planned to include equipment with 150% continuous overload capacity. The total cost estimate for the HVdc converter stations and electrodes based on an AACE Class 4 estimate are reasonable for DG2 purposes. The costs for the synchronous condensers are low but are still within the range of an AACE Class 4 estimate. For the purposes of developing a cost estimate comparison, MHI used data from similar prior projects.

6.11 Risk Review

There does not appear to be any risk analysis done for the HVdc converter stations or the operational aspects of the Labrador-Island Link HVdc system. Converter station outages could be lengthy and could be very costly to repair particularly if lost revenues are considered. MHI recommends that this be completed prior to the development of the HVdc converter station specification so any additional requirements can be included.

6.12 Conclusions and Key Findings

The assessment of the technical work done by Nalcor on the HVdc converter stations, electrode lines, and associated switchyard equipment was undertaken by MHI as part of its technical review of the two options. Most project documentation on the Labrador-Island Link HVdc system was not available, such as the HVdc converter station single line diagram or a concept transition document, since the project definition changed in November 2010 with DG2. This lack of detailed information on the revised HVdc system hampered MHI's review.

MHI notes that there was no comprehensive HVdc system risk analysis review of operations and maintenance for the overall HVdc transmission system including converter station equipment, transmission lines, or converter station control, protection and communications. MHI recommends that this operational design risk analysis be completed in conjunction with the development of the HVdc converter station specification so that any additional requirements may be included.

Key findings from the review of the HVdc converter stations, electrode lines, and associated switchyards are as follows:

- MHI found that the HVdc converter station system design parameters available for review are reasonable for the intended application. The intended application is to transmit 900 MW of firm power over 1100 km of transmission line and inject this power into the island's electrical system at Soldiers Pond with appropriate voltage and frequency control.

- The Labrador-Island Link design progression has specified LCC (line commutated converters) HVdc technology, which is mature and robust for the application.¹⁵⁸ However, the response to RFI MHI-Nalcor-67 has indicated that VSC (voltage sourced converter) options will be considered if there are technical and financial advantages to do so. It is important to note that VSC systems of the size and length of the Labrador-Island Link HVdc system have not yet been built and operated anywhere in the world as of the issue date of this report.
- The estimate for the HVdc converter stations and electrodes was reviewed by MHI and found to be within the range of an AACE Class 4 estimate. The cost estimates for the synchronous condensers are low but are still within the range of an AACE Class 4 estimate.

¹⁵⁸ Exhibit 30, Nalcor, "Technical Note: Lower Churchill Project Design Progression 1999 to 2011", July 2011