Review of
Newfoundland and Labrador Hydro
Power Supply Adequacy and Reliability
Prior to and Post Muskrat Falls
Final Report

Executive Summary

Presented to:

The Board of Commissioners of Public Utilities
Newfoundland and Labrador
Presented by:

The Liberty Consulting Group

August 19, 2016

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Executive Summary

Background to Liberty's Examination

- The Board of Commissioners of Public Utilities ("Board") initiated an inquiry and investigation into the circumstances leading up to and surrounding power outages that occurred in January 2014 on the interconnected electrical system serving customers on the island of Newfoundland ("IIS"). The scope of this investigation includes the adequacy and reliability of the IIS over the short, medium and long term, including the implications of the interconnection with Muskrat Falls.
- The Board retained The Liberty Consulting Group ("Liberty") to assist in the investigation. Liberty filed an interim report in April 2014 on the causes of the 2014 power outages and identified priority actions to be taken by Newfoundland and Labrador Hydro ("Hydro") and Newfoundland Power to reduce the risks of future outages in the short term. In December 2014 Liberty filed a report that confirmed the causes of the 2014 power outages, reviewed the actions taken by the utilities in response to the recommendations in its interim report, reviewed Hydro's various processes and asset management activities as they concern efforts to sustain reliability and made a number of recommendations to enhance reliability.
- This report provides Liberty's assessment of the adequacy and reliability of the IIS to meet customers' load both up to and after the interconnection with Muskrat Falls. It provides a detailed examination of the components of the Muskrat Falls interconnection and Liberty's opinion on how the components and the overall system will affect reliability and the adequacy of power for the IIS after the interconnection. It also reviews circumstances, including events that have occurred with the availability of Hydro's thermal units since Liberty's 2014 reports and assesses the implications for the adequacy and reliability of the IIS until the interconnection.
- Liberty has extensive experience working with utility regulators on a full range of areas involving the provision of safe, reliable and cost effective utility service. Liberty has worked for regulators in some 40 North American jurisdictions and has undertaken work for a similar number of North American energy utilities.

Liberty's Major Conclusions

- Our review concludes that the interconnection of the IIS with Muskrat Falls and the Maritime Link can represent a state-of-the-art electrical system whose reliability is improved over today's circumstances. More work will be needed to assure that accomplishment, however, including two major features that Hydro is not necessarily considering at this time. Those features are (1) additional power supply and (2) expanded organizational capabilities.

- Continuing problems with Hydro's existing thermal generating units and the delay in the in-service date for Muskrat Falls increase the risk of outages until the interconnection.
- While it had long been contemplated that Muskrat Falls would preclude the need for more supply until the 2030s, this is not likely to be the case. Liberty expects that new supply will be needed *before* Muskrat Falls is in service, to mitigate near-term supply issues, and *after* Muskrat Falls is in service, to mitigate the impact of extended outages of the Labrador-Island Link (LIL). This additional supply can be sourced through firm purchases, if available, over the Maritime Link or additional new generation on the IIS.
- In addition, in analyzing system reliability, one should remember that many of Hydro's past issues, including the major outages in 2013 and 2014 and the voltage collapse of 2015, were as much or more due to organizational issues as they were due to system inadequacies. The new investment will not eliminate those organizational issues, or the outages that flow from them. It is therefore urgent that Newfoundland's investment be protected and optimized with improvements to Hydro's operating, planning, and other technical capabilities.

<u>Need for Added Power Supply - Pre - Muskrat Falls</u>

- In its 2014 report Liberty concluded that the 2014 outages were caused by two different factors: (a) insufficient generating resources on Hydro's system to meet customer demands and (b) failures of key Hydro transmission equipment. Liberty also found that despite the addition of new generation (a 120 megawatt combustion turbine), and capacity assistance agreements with certain industrial customers, generation reserves were low and the risk of outages remained high for the 2015-2017 winter seasons. Effective management of Hydro's existing generation resources would be required to mitigate the high risk of outages.
- Major 2015-2016 failures on Hydro's thermal units, including the Holyrood generating units and the combustion turbines at Hardwoods and Stephenville, significantly impacted the amount of generation available to meet customers' needs. At this time, repair work is ongoing at Holyrood and there is uncertainty about the future full availability of the capacity of these units. In addition, even if these units are returned to full rated capacity, there is continuing uncertainty, given their age, condition and past performance, on the ability to rely on them for the future until the interconnection with Muskrat Falls.
- In June 2016, it was announced that the full in-service date for Muskrat Falls, which was originally planned to be in-service for the winter of 2017-18, has been delayed until the winter of 2020-21. This considerably extends the time that the existing thermal units must be available.
- Hydro's recent assessment of supply adequacy until the interconnection indicates reliability violations which Hydro proposes to mitigate but not eliminate. Liberty believes the supply risks are greater than suggested by Hydro's assessment and that new generation is likely required prior to the interconnection.

Need for Added Power Supply - Post-Muskrat Falls

- The IIS is a relatively small system, approximately 1,700 megawatts, with the majority of its load centered on the Avalon Peninsula. The size of Muskrat Falls (824 megawatts) and the associated delivery capacity, the LIL, is large for the size of the IIS. This presents challenges from a reliability perspective given the consequences of the instantaneous loss of the LIL. Hydro's system design seeks to minimize the potential for outages, but outages cannot be completely avoided.
- The LIL design includes many reliability features, including many redundancies. A key feature is that it essentially functions in two halves, called poles, which have been designed with overload capacity so that if one pole is out of service, a significant amount of power can still be delivered to the IIS. This feature and others are discussed in detail in the report and Liberty makes a number of recommendations to further enhance reliability.
- If a bipole (both poles) trip of the LIL is more than momentary, the loss of power from the LIL will result in under-frequency load shedding. Reliability analyses completed by Hydro for the LIL indicate a probability of a full LIL outage every three years with an average duration of twenty-nine hours. With sufficient backup supply, the duration of customer outages will be limited to a few hours, regardless of the length of the LIL outage. Liberty believes, however, that there will be more LIL bipole outages than estimated by Hydro.
- If there is not sufficient backup supply, there will be additional customer impact, including likely rotating outages for the balance of the LIL outage. Liberty recommends that strategies be implemented that contain loss of load on a bipole trip to limited under-frequency load shedding. In other words, adequate backup capacity should be available to prevent extensive and extended loss of load on loss of the LIL.
- Adequate backup capacity will be new combustion turbines or firm, dependable capacity from Nova Scotia via the Maritime Link. Liberty recommends that Hydro secure the necessary capacity commitments to mitigate the consequences of an extended LIL bipole outage.
- Extended LIL outages are possible, including failure of the overhead line. Although Hydro's stated objective is to complete repairs for the overhead lines within two weeks, it is difficult to have confidence that two weeks is the maximum limit for an OHL-related outage, recognizing the magnitude of the challenge of repairing significant OHL damage in potentially extreme weather and in harsh terrain.

Role of the Maritime Link

- Hydro's reliability analyses assume the Maritime Link is equivalent to a 300 MW generator with high availability for the IIS. The benefits of the ability to curtail the Maritime Link in the event of problems with the LIL are shown by the analyses to be considerable. The Maritime Link is thus a critical feature for the operation and reliability of the IIS. The Maritime Link is also a potential source of power to meet the load on the IIS.

- The Maritime Link is one of the effective tools for mitigation of LIL outages. On a loss of the LIL, the power flow over the Maritime Link will be immediately stopped so that the loss of load to the IIS will be the LIL power minus the Maritime Link load. This is not enough to prevent under-frequency load shedding on the IIS at high load.
- Liberty recommends that, given the criticality of the Maritime Link to the reliability of the IIS, additional studies be completed not only with the Link in service, but also with it out of service.
- On a bipole trip, Nova Scotia will have to replace the power it loses from Muskrat Falls and provide additional capacity for the IIS. The extent to which reliance can be placed on the Maritime Link as a source of dependable generation and the competitiveness of such supply are not certain at this time.

Transition to Operations Post Muskrat Falls

- The challenges facing Hydro with the interconnection to Muskrat Falls include adding a large generator to a relatively small system, new HVdc technology, and interconnection with the North American grid. Liberty considers these challenges so far reaching that they will substantially alter the identity of Hydro and require a major transformation of the company.
- Liberty has in its past work for the Board identified deficiencies in Hydro's operating culture and its approaches to planning, reliability analyses, system operations and asset management. Liberty considers it essential that a detailed plan be developed to address these issues. These issues must be addressed in a substantive way if there is to be successful, reliable operation of the LIL after interconnection.
- Hydro has established a number of transition teams whose work seems primarily limited to planning initiatives at this time and whose efforts are impeded by inadequate staffing. Liberty recommends that the schedule be given heightened focus and that appropriate resources be assigned.
- One focus for the transition teams is development of current staff to acquire the new skills required. Liberty believes that external resources with the necessary skills will also have to be recruited and recommends that Hydro develop a plan to do so.
- There are a considerable number of significant studies and plans to be completed whose results will affect the operation of the LIL. Every effort must be taken to ensure that they are completed in a timely way.

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I. Introduction

A. Background

In December, 2012, the Government of Newfoundland and Labrador sanctioned the construction of the Muskrat Falls project which includes an 824 MW hydro plant at Muskrat Falls, in Labrador and a 1,100 km high voltage dc line from Muskrat Falls to the Avalon Peninsula, including a 30 km subsea section crossing the Strait of Belle Isle. The dc line is known as the Labrador-Island Link (LIL). The line and the hydroelectric facility at Muskrat Falls are together referred to in this report as Muskrat Falls. Muskrat Falls is intended to meet the future power needs of the interconnected electrical system serving customers on the island of Newfoundland (the "IIS") and was originally scheduled to be in-service in late 2017 with full power in 2018.

Another component of the Muskrat Falls project is the Maritime Link which is a high voltage dc line of approximately 360 km, including a 180 km subsea cable under the Cabot Strait, connecting the island of Newfoundland to Nova Scotia. Energy from Muskrat Falls will be sold to Nova Scotia over the Maritime Link.

The IIS experienced significant outages in 2013 and 2014. In January 2013 a series of events on the system of Newfoundland and Labrador Hydro ("Hydro") caused extensive outages primarily for customers on the Avalon Peninsula. The following year in January 2014, conditions on Hydro's system caused two series of outages from January 2 - 8 with the first due to a shortage in availability of Hydro's generating resources and the second due to transmission equipment failures. Rotating power outages were implemented commencing on January 2 to address the generation deficit and as the utilities were recovering from these outages, equipment failures on Hydro's transmission system caused additional widespread uncontrolled outages and another series of rotating outages. Newfoundland Power, the primary distribution utility on the IIS, was also impacted in both years as it purchases most of its power from Hydro.

On January 10, 2014 the Board of Commissioners of Public Utilities (the "Board") initiated an inquiry and investigation into the circumstances leading up to and surrounding the 2014 power outages and system disruptions. The Board determined that the investigation would address the adequacy and reliability of the IIS over the short, medium and long term, including the implications for the IIS of the interconnection with Muskrat Falls. The identification of actions necessary to enhance preparedness for the upcoming winters of 2014-2015 and 2015-2016 was determined to be a priority to be addressed first. The Board retained The Liberty Consulting Group ("Liberty") to assist with the investigation.

Liberty filed an interim report, as requested by the Board, on April 24, 2014 ("Interim Report") which addressed the causes of the IIS events in 2013 and 2014 and recommended system changes to enhance preparedness in the short term, 2014 to 2016, to reduce the risk of further outages.

In October 2014 the Board determined that the scope of the investigation would be dealt with in two phases, with the first addressing the adequacy and reliability of the IIS up to the interconnection with Muskrat Falls and the second dealing with the implications of the interconnection for the adequacy and reliability of the IIS.

On December 17, 2014 Liberty issued two reports, one for Hydro and one for Newfoundland Power, on the causes of the 2014 power outages and system disruptions, the responses of the utilities to the recommendations made in Liberty's Interim Report and longer term issues affecting reliability until the interconnection with Muskrat Falls. This report was intended to be Liberty's final report in phase one of the investigation which was originally planned to include the adequacy and reliability of the IIS until the interconnection with Muskrat Falls.

Since Liberty's December, 2014 reports circumstances have arisen on Hydro's system, including continuing issues with its thermal assets, which have implications for the adequacy and reliability of the IIS until the interconnection with Muskrat Falls. The Board determined that the issue of adequacy and reliability of the IIS until the interconnection should be included as part of the scope of the phase two investigation and requested that Liberty consider this new information to determine how it affects Liberty's opinions and conclusions expressed in its December, 2014 report on Hydro ("2014 Report").

In 2015 Liberty also reported to the Board on two additional matters concerning Hydro and the IIS. The first addressed the causes of a March 2015 outage on Hydro's system and recommended a number of remedial actions ("Liberty's March 2015 Outage Report"). The second dated July 6, 2015, concerned the prudence of certain actions by Hydro ("Liberty's Prudence Report") which were primarily related to the 2013 and 2014 outages and their associated costs which Hydro was seeking to include in its revenue requirements in its general rate application proceeding. The work Liberty completed in these matters contributed to its knowledge and understanding of Hydro's management philosophies, its asset management practices, and its approach to reliability, operations and supply planning and assisted in the work Liberty completed for this report.

B. Scope of This Report

Liberty's 2014 Report concluded that despite adding new generation, an improved winter readiness program and new capacity assistance agreements with certain industrial customers, power supply on the IIS remained tight with very low generation reserves and the risk of outages remained high. This report presents our review, as requested by the Board, of the events that have occurred since our December 2014 report concerning the adequacy and reliability of the IIS to supply customers until the interconnection with Muskrat Falls. The concerns expressed in our 2014 Report have been heightened as a result of these new events that primarily concern Hydro's thermal generating units. We believe, based on the current Hydro analysis, that the risk of supply-related outages until the interconnection is high. It is essential that this risk be effectively managed. We make a number of recommendations to enhance the management of this risk to reduce the potential for extended customer outages.

This report also presents the results of our assessment of the integration of the LIL and the Maritime Link into the IIS. As directed by the Board for the scope of the phase two investigation, we did not address detailed technical information or project engineering and construction issues, except as necessary to understand the reliability risks associated with the interconnection to the IIS. Neither were the design of the generating facility and the cost and schedule of the project reviewed, except as necessary to understand the power supply risks of delays.

From an electrical perspective the introduction of a large amount of power landing at one point in a relatively small system, such as the IIS, raises questions of stability and reliability which are addressed in this report. The Maritime Link, providing an interconnection to the North American grid, can mitigate these concerns and has the potential to provide reliability enhancements for the IIS, opportunities for purchases and sales of electricity and sharing of reserves among other utilities. As discussed in this report, the successful operation of both Muskrat Falls and the Maritime Link is essential for the adequacy of supply and the reliability of the IIS.

This report covers the following areas:

- **Power Supply Adequacy and Reliability Pre-Muskrat Falls.** Delays in Muskrat Falls and deteriorating performance of Hydro's thermal units make the question of supply adequacy pre-Muskrat Falls of critical importance. (Chapter II)
- **The LIL and the Maritime Link.** The design features of the LIL and the Maritime Links and how the design features affect reliable integration with the IIS are discussed. (Chapter III)
- **Reliability of Muskrat Falls.** Reliability of LIL components and the system as a whole are also addressed. (Chapter IV)
- **Power Supply Adequacy and Reliability Post Muskrat Falls.** Reliability will continue to be a concern for customers after the interconnection with Muskrat Falls. Firm imports over the Maritime Link and/or additional generation most likely will be required. (Chapter V)
- **Transition to Operations.** The Hydro organization faces a major challenge in preparing to take operational responsibility for the new assets. Much remains to be completed to ensure this transition goes smoothly and effectively. In addition, there have been reliability concerns in the past few years, and much remains to be done to ensure that the new assets will be managed reliably and for stakeholders to have confidence that Hydro will do so. (Chapter VI)

Conclusions and recommendations are set out in each section in the report and are then summarized in Chapter VII.

C. Liberty's Team and Process

Liberty has worked with most of the regulatory commissions in the United States and a number in Canada. Liberty's team for this project included two individuals who participated in all previous work for the Board, John Antonuk and Richard Mazzini, each of whom has more than thirty-five years of utility regulatory experience. Mr. Antonuk is Liberty's president and one of the firm's founders. He received a bachelor's degree from Dickinson College and a juris doctorate from the Dickinson School of Law. He has led in excess of 300 projects for Liberty. Mr. Mazzini received a B.E.E. (Electrical Engineering) degree from Villanova University and an M.S. degree in Nuclear Engineering from Columbia University. He has managed several broad management audits of large electric utilities for Liberty. Dr. Bjarne Andersen, a highly regarded international expert in the field of HVdc technology, joined the team to provide specific HVdc expertise. Dr. Andersen is President of Andersen Power Electronic Solutions Ltd and is based in East Sussex, UK.

A more complete description of the credentials of the team is in Appendix A.

The Liberty team met with Board staff and Hydro management to identify the issues to be reviewed in this phase of the investigation. Formal requests for information were asked and Liberty reviewed the responses to them. As well, Liberty conducted interviews with Hydro management and other personnel to further explore issues and obtain clarification as necessary.

II. Power Supply Adequacy and Reliability Pre - Muskrat Falls

The adequacy and reliability of power supply on the IIS until the interconnection with Muskrat Falls was a major issue addressed in phase one of the investigation. Liberty reviewed in detail Hydro's power supply planning practices, asset management practices and operational management practices regarding generation availability and reliability. Liberty made a number of recommendations, which Hydro generally accepted, in its Interim Report and its 2014 Report to improve and enhance these practices.

Liberty concluded in its 2014 Report that, although new generation had been added and other measures implemented, the risk of outages on the IIS remained high for the next winter seasons until the planned interconnection with Muskrat Falls, which was then scheduled for the 2017-2018 winter. This risk required that Hydro effectively maintain its existing generation resources, continuously review its supply planning assumptions and take additional actions as necessary to ensure it could reliably supply customers.

The power supply picture has, however, changed dramatically since Liberty's 2014 Report. In early 2016, Hydro's thermal units experienced failures which raise concerns on the ability to continue to rely on these units. In addition, a more than two-year delay in the in-service date for Muskrat Falls was announced.[1] Liberty at the request of the Board has reviewed the adequacy and reliability of supply for the IIS until the interconnection in light of these significant changes.

In Liberty's opinion, Hydro must seriously consider the need for new supply prior to the interconnection with Muskrat Falls and should develop plans accordingly. In addition, Hydro should also undertake as soon as possible an in depth review of its current supply planning practices, processes and capabilities in order to develop stronger enhanced skills and capabilities.

A. Background

In January 2014, Hydro suffered widespread system failures that resulted first from a shortage of supply that led to rotating outages, followed by major electrical equipment failures that took out large parts of the system. Liberty's Interim Report in April, 2014 concluded that "a continuing and unacceptably high risk of outages from such causes remains for the 2015-2017 winter seasons". Hydro took a number of substantive actions to address the capacity deficit including:

- New generation, which took the form of a 120 MW CT installed during 2014.
- New interruptible load, which took the form of a 60 MW contract.
- More aggressive maintenance and investment in power plants to enhance availability.

These actions were expected to provide relief from the near-term supply threats, but Liberty's opinion on the adequacy of these actions to address the issue changed later that year following the completion of its review. Liberty issued its 2014 Report on December 17, 2014, concluding that, despite the new generation and interruptible load, "generation reserves are very low and the risk of outages remains high for the 2015-17 winter seasons." This conclusion resulted from

[1] The current availability of full power from Muskrat Falls is forecast as "mid-2020", which is in time for the winter of 2020-21. This contrasts to the original plans of the winter of 2017-18.

changes, which Liberty agreed were appropriate, in Hydro's planning approach. These changes, which offset the added supply with more demand, included:

- A shift to a 90% probability for the peak demand forecast from Hydro's previously used 50%.
- Realization that Hydro's assumptions regarding loss of load hours and thermal unit availabilities produced inadequate reserves.
- Corrections in the assumptions regarding system losses in abnormal operating conditions.

In late 2014, the IIS was therefore in a situation where supply challenges remained, but for which two of the three mitigation options (new generation and new interruptible load) had already been employed. The third, and only remaining, mitigation possible was effective management of generating unit availability. While risk remained, there was an expectation that reserves would be sufficient given suitable performance of Hydro's generation fleet.

Figure II.1: Forces Driving the Need for New Pre-Muskrat Falls Capacity

Holyrood Unavailability

Hardwoods and Stephenville Unavailability

Further Muskrat Falls Delays

Major 2015-16 winter failures on Holyrood Units 1 and 2, and the combustion turbines at Hardwoods and Stephenville significantly impacted the amount of generation available to meet customers' load. The uncertain future of the availability of the full capacity of these units seriously erodes confidence in their future as reliable generation resources until the interconnection with Muskrat Falls. Further, Hydro has announced that Muskrat Falls generation will be delayed, with synchronization in late 2019 and full load in time for the winter of 2020-21. These new circumstances raise serious concerns on pre-Muskrat Falls supply adequacy, producing significant consequences for Hydro and its customers.

B. Hydro's Analysis of Supply Adequacy Pre - Muskrat Falls

Hydro recently (May 2016) completed an "Energy Supply Risk Assessment" which is critical to understanding the near-term threats to power supply.

Supply reliability discussions at Hydro have traditionally focused on loss of load hours (LOLH). Hydro has set a maximum of 2.8 for many years. This value is the equivalent of one failure to meet demand in five years. Most utilities in North America work to a standard of once every ten years.

An outcome of Liberty's 2014 Report was that a consideration of reserve margins, which is another measure of supply reliability, is also necessary. Liberty's examination of reserves suggested that, although the LOLH target was being met, reserves seemed too low. Hydro subsequently filed additional information and agreed to include reserves in its planning and has set a short-term target for reserves of 240 MW.

In its most recent analysis, Hydro introduced a third measure of supply reliability. Expected unserved energy (EUE) is the amount of energy not supplied due to supply-related emergencies. Hydro has done further analysis to equate an EUE of 300 MWh to an LOLH of 2.8 hours[2].

[2] "Energy Supply Risk assessment", May 2016, Page 7

The use of three measures contributes to an understanding of the dynamics of supply reliability. But inevitable inconsistencies among the measures also lead to complications. For example, Hydro has indicated that the LOLH target has rarely been threatened. Yet, if the EUE equivalent is used, Hydro has not met the target in four of the last five years, and barely met it in the fifth year (and that was due to the new CT). The accompanying chart shows this phenomenon. Further, we have seen previously that the LOLH can translate into inadequate reserves. This is simply further evidence that the LOLH, although widely used by utilities, has its limitations, particularly if considered in isolation of other factors.

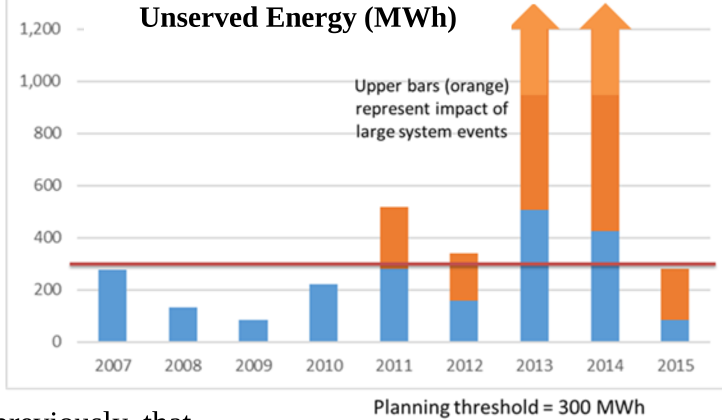


Figure II.2: Historical Unserved Energy (MWh)

1. Thermal Unit Availability

a. Holyrood Boiler Tube Failures

Hydro's analysis of reliability, whether measured in LOLH or EUE, demonstrates that it is driven primarily by the unavailability of the Holyrood units.

The three Holyrood units employ oil-fired boilers. These are large furnaces whose walls and interior are lined with metal tubes through which water flows. As the water passes through the tubes, the heat from the furnace converts it to steam. Multiple passes of the fluid through various sections of the boiler add further heat to (a) the original steam flow (superheater sections), (b) steam exhausting from the high pressure section of the turbine for re-entry into a subsequent lower pressure section of the turbine (reheat sections), and (c) the feedwater, pre-heating it (economizer sections).

Tube leaks raise a typical concern in all boilers. In a well-maintained boiler, where corrosive effects on the tubes are guarded against and in which water quality is religiously maintained, tube failures can be limited. Hydro did experience corrosion issues in past years due to fuel quality; however, there has been no major issue with the level of tube failures at Holyrood through the years.[3] In fact, there was only one tube failure among all three units in the 2011-15 period.

Another source of tube failures is age. After many years of high temperature and high pressure service, the tube walls become thinner. This is a natural evolution and boiler sections are occasionally re-tubed as a preventive measure.[4]

[3] PUB-NLH-601
[4] Hydro is re-tubing certain sections of the Units 1 and 2 boilers in the summer of 2016.

While tube failures are by no means unusual, it is quite unusual for large scale failures across sections of the boiler. Multiple tube failures can occur, either through neighboring tubes failing or through high pressure fluid impingement from one failed tube directed at others. But the failing of many tubes and the immediate threat of many more failing, as is the case at Holyrood, is unusual.

The failed tubes in Holyrood Units 1 and 2 in early 2016 all occurred in the lower reheat sections of the boiler, which location and conditions make them more susceptible to failure according to Hydro's initial analysis.[5] That analysis suggested that the boilers remain susceptible to inordinate numbers of tube failures in the future. As a result, Hydro decided to de-rate all three units at Holyrood to mitigate the probability of future tube failures.

After its initial analysis, Hydro retained Amec Foster Wheeler to complete a more detailed assessment.[6] The conclusions of that assessment were quite different, including an observation that "there is a low risk of boiler tube failures due to wall thinning on Units 1 and 2, operating at current pressure, with no de-rate, to 2021". The Unit 3 assessment was more pessimistic, concluding that "there is a high risk of tube failures due to wall thinning within the next year." Amec Foster Wheeler qualified its conclusions as follows:

- The conclusions consider only boiler tube wall thinning and do not consider other potential reliability risks (*e.g.*, fatigue). In this regard, limiting stops/starts and load cycling was recommended.
- Hydro should seek concurrence of the boiler and pressure vessel jurisdictional authority.
- Additional tube replacements on Unit 3 are required as soon as possible, with a 10% de-rate employed in the interim. Hydro plans to do this work in the summer of 2017.
- Annual boiler tube wall thickness surveys should be continued.

Compared to Hydro's initial concerns, the Amec Foster Wheeler report is a very encouraging result. The planned de-rate is far less than originally implemented and the high level of concern regarding future Unit 1 and 2 failures has been largely eliminated. This is good news by any measure. It is far from clear, however, if the perceived "improvement" in the reliability of Holyrood is sufficient to eliminate a need for new pre-Muskrat Falls supply.

The measure of unavailability used by Hydro is DAFOR, which reflects an equivalent forced outage rate. A traditional forced outage rate measures the time the unit is off versus on. This approach gives the unit full credit for operating even if it is only at part load. On the other hand, the DAFOR gives only partial credit when the unit is at part load. For example, if a unit is forced to run at only 75%, 25% of the associated hours count as a forced outage.

[5] "Units 1 and 2 Boilers Lower Reheater Tube Replacement and Reliability Improvements", March 2016, Page 8, Line 15
[6] Amec Foster Wheeler August 8, 2016 letter to Nalcor "Re: Holyrood TGS Boiler Tube Thinning Assessment"

Past Hydro analyses assumed a DAFOR of 10% for each of the Holyrood units. The events of this past winter suggest that such a figure is too optimistic. Rather than estimating a new DAFOR, Hydro has conducted sensitivity studies with Holyrood DAFORs of 10%, 14%, 19% and 24%. This is an appropriate approach, given that the condition of the units at the time of the latest supply assessment was highly uncertain. The assumption that DAFOR will be worse than 10%, and perhaps significantly so, is reasonable. Presumably, Hydro's next supply assessment, which we recommend be completed in the near term, will incorporate the results of the Amec Foster Wheeler report and settle on a reasonable DAFOR for each Holyrood unit.

b. Hardwoods and Stephenville Combustion Turbines

Liberty in its past reports has expressed concerns about relying on the Hardwoods and Stephenville combustion turbines (CTs) as reliable sources of capacity. In its December, 2014 report Liberty expressed concern about the vulnerability of these units given their forced outage rates and the problems with them up to that time. In its Prudence Report in July 2015, Liberty noted that the Hardwoods unit was particularly unreliable with its Utilization Forced Outage Probability (UFOP) rate averaging over 26% over the period 2008 to 2012. These concerns have been heightened by subsequent events.

In early 2016, the Hardwoods and Stephenville CTs both failed, within six weeks of one another. Reliance on these machines has been an issue in each of the last three winters as follows:

- In 2014 Hardwoods was late returning from an outage. When it did return, the unit failed on startup due to a fuel control valve failure, rendering the unit fully unavailable during the January outages. Meanwhile, Stephenville was in a debilitated state due to returning from a prolonged outage in which necessary insulation was not procured, resulting in a 25 MW de-rating. In December 2013, the unit was totally unavailable when parts were scavenged to facilitate the return to service of Hardwoods. At the time of the January outages Stephenville was available at only 25 MW, or half load.
- In 2015, a fire at Hardwoods made that unit unavailable for part of the winter, while faulty fuel lines at Stephenville made that unit partially unavailable for part of the winter.
- In 2016, both units suffered engine failures.

These examples resulted in reduced available time for the units. In addition, these units are not especially reliable when available and called to start. Whether unavailable, or available but failing to start, the end result is the same – the units are not dependable sources of capacity.

We note that each unit has undergone life extension programs, Hardwoods in 2009-13 and Stephenville in 2014-16 (still in process). In addition, an engine was overhauled at Hardwoods in 2015. Hydro has, therefore, made investments in these units, and expects them to last at least another ten years, although they are already beyond their originally intended life. Hydro reports that average useful life is 35 years, compared to their current ages of about 40 years, but notes that many of the operating hours for the units have been in synchronous condensing mode, which would be expected to prolong their lives.[7] The failure of both units during each of the last three winters gives a strong basis for concern that the chances this capacity will be there when needed

[7] "Gas Generator Engine Refurbishments", May 2016, Page 12.

are not good. Any capacity assessment that assumes a good chance of both units starting when needed must be considered questionable in our opinion.

c. Results of Hydro Analysis

The Hydro assessment indicates that Hydro's reliability criterion (EUE ≤ 300 MWh) is exceeded in the next two winters for Holyrood DAFORs ≥ 14%. With DAFORs of 19% and higher, the violation extends for the next four winters, at which time Muskrat Falls generation is assumed to be available. Hydro currently plans to accelerate the construction of a new transmission line (TL267) between Bay d'Espoir and Western Avalon, and expects this addition to eliminate the violation in the winter of 2017/18, but not other years if DAFOR is 19% or higher. Hydro also purchased 10 MW of the 12 MW black start diesels it had previously leased at Holyrood. The response to IC-NLH-053 shows that this addition results in lower values for EUE but does not eliminate the violations with DAFOR at 19% or higher.

Loss of load scenarios cannot be predicted with certainty, nor with highly accurate probabilities. This is a question of risk, and the data indicates that the risk at this time, and for the next 2-4 winters, is greater than previously thought and is more than Hydro would like. This does not mean that such risks are automatically unacceptable. One must balance the risk against the cost of new capacity to make an informed decision. Hydro can and should do that analysis as soon as possible. This is especially important in that we believe that future supply risk is greater than that presented in Hydro's assessment. There are several reasons why we consider the risk to be higher than calculated by Hydro:

- The Holyrood situation, which is the primary driver of Hydro's recent supply adequacy assessment, has considerable downside potential. The Amec Foster Wheeler study mitigates this concern for one particular failure mechanism, but the history and age of the units nevertheless creates exposure. Holyrood was intended to stay in operation until 2020 when Muskrat Falls was scheduled to be in full service in 2018. This is not the case now and Holyrood will be required beyond 2020 until at least 2022, assuming that Hydro maintains its plan to overlap Muskrat Falls and Holyrood for several years. The condition of the aged Holyrood units raises significant concern that these units will be able to stay in operation at full capacity for this extended period.

- As discussed above, the Hardwoods and Stephenville units continue to be unreliable despite new investments. As the units age further, it is reasonable to assume that the situation with these units will worsen.

- The forecast for peak demand is a critical estimate for determining supply needs. Hydro traditionally used a P50 forecast, meaning there is a 50% chance that the actual peak load in a given winter will exceed the P50 value. In its Interim Report, Liberty recommended the use of a more conservative forecast and Hydro agreed to examine a P90 forecast as a sensitivity case. Since that time, Hydro has presented its analyses assuming both cases, P50 and P90. The P90 case results in a peak demand about 60 MW higher than the P50 case. In its examination of Hydro's report, Liberty has focused on the P90 assumption since the notion of planning to a peak that will be exceeded in half the years is not, in our opinion, a prudent practice.

Hydro also stated that its economic outlook for the province indicates that depressed economic activity will produce lower loads. This result would produce a lower forecast for peak demand. We note that the theorized reduction projected by Hydro is significant, on the order of 30 MW, but that it does not change the results greatly.

The P90 forecast used in the Hydro analysis has fallen significantly from its year-ago value. Winter peaks are now forecast to be about 50 MW lower than previously thought. In addition, forecasted year-over-year growth has fallen. The interesting result is that the peak now forecasted for 2020 is about 20 MW less than the peak previously forecasted for 2016.

Figure II.3: Forecast of Peak Demand (P90)

	Winter of:				
	2016/17	2017/18	2018/19	2019/20	3-Yr. Change
June 30, 2015	1,846	1,868	1,868	1,881	1.9%
April 4, 2016	1,801	1,831	1,819	1,827	1.4%
Change	-45	-37	-49	-54	

This major shift eases the perceived supply situation. But the question raised is whether such a large reduction in the forecast in such a short period is credible and whether it will actually materialize. If this significant reduction in load does not happen, then the risk of supply-related interruptions will be higher.

Hydro has explained this change in PUB-NLH-598. The primary factor cited is a reduction in Vale load. Interestingly, other industrial load is forecast to increase, somewhat offsetting the Vale reduction. Hydro specifically notes that the Vale reduction was for the winter of 2016-17, leaving its applicability to future years in question.

The second largest factor is Newfoundland Power's forecast, which Hydro attributes to "lower system load growth".

Pending an opportunity for further analysis of Hydro's load forecast, one must conclude that there is exposure here for load being higher than assumed in Hydro's capacity analysis.

Each of the risk factors discussed above has the effect of increasing the risk that Hydro's current supply assessment is overly optimistic and that new supply will be needed sooner rather than later. An additional consideration is that the criteria violation is related to the 2.8 LOLH (or 300 EUE). If new criteria more consistent with North American practice are adopted, these limits would be reduced and hence violations increased.

C. Solution

In summary, Liberty believes that the need for pre-Muskrat Falls supply is likely. Reliability violations are already forecast by Hydro, and could be worse if Liberty's concerns with Hydro's analyses are correct. In addition, the Hardwoods and Stephenville units are undependable and will likely have to be replaced. And with more than four years remaining before Muskrat Falls is in service, there is exposure to further delays. Finally, we will demonstrate later in this report that added supply is likely needed *after* Muskrat Falls is in service as well, further justifying any near-term decision in that regard.

New pre-Muskrat Falls supply would not necessarily take the form of new investment in combustion turbines. Power can be imported on both the LIL and the ML when those lines are in-service. Hydro informs that it could import 110 MW of firm recall power from Labrador and 300 MW from Nova Scotia.[8] This would likely solve the pre-Muskrat Falls supply issue, but we note that neither the technical feasibility of the LIL/recall power solution nor the availability of Nova Scotia capacity have been validated at this time.

D. Conclusions

II-1. The IIS remains vulnerable to supply-related disruptions until Muskrat Falls and the LIL begin reliable operation.

II-2. The Holyrood oil-fired units and the Hardwoods and Stephenville CTs, which have performed poorly, are primarily responsible for the system's vulnerability.

II-3. Hydro's recent assessment of supply adequacy indicates reliability violations which Hydro proposes to mitigate but not eliminate.

II-4. Liberty believes that supply risks are greater than suggested by Hydro's assessment.

II-5. Liberty believes that a more detailed pre-Muskrat Falls supply assessment, including adequate consideration of the risks, is likely to conclude that new supply is required in the near future.

E. Recommendations

Recommendation II-1. Hydro should conduct a new supply review that considers all risks, including the thermal assets and the planned reductions in the load forecast, and provide a risk-based recommendation on the need, timing and amount, if any, for new pre-Muskrat Falls supply.

[8] "Energy Supply Risk Assessment", May 2016, Page 20

III. The Labrador-Island Link and the Maritime Link

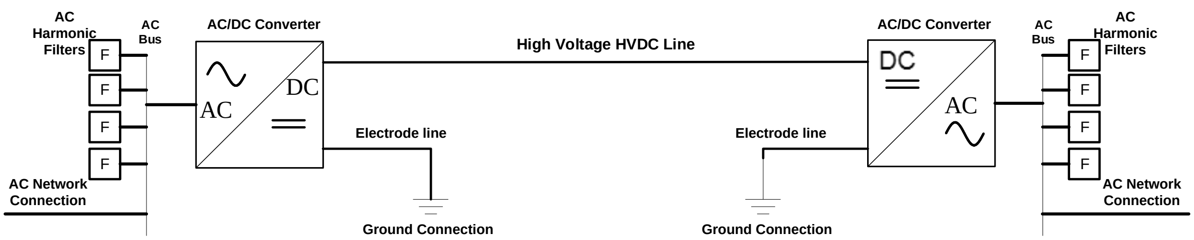
A. Introduction to HVdc Transmission

This section provides a brief and simplified description of HVdc transmission, which is a central feature of the Muskrat Falls project.

An HVdc scheme delivers electrical power from one location to another. HVdc Converter stations convert the power from ac to dc at one location and vice versa at the other location. Power electronic converters perform these conversions at both ends.[9] A control system controls the power electronic converters, enabling determination of the power flow between the terminals at the level set by the system operator.

Figure III.1 presents a simplified diagram of an HVdc scheme.

Figure III.1: Simplified HVdc Scheme



The configuration shown in Figure III.1 is called a Monopolar HVdc scheme, because it consists of only one power block. The Figure shows the connection of the two ac/dc converters by means of a High Voltage HVdc line[10] consisting of an Over Head Line (OHL),[11] a cable, or a combination of the two. The ac/dc converters are also connected through Electrode Lines to Ground[12] at locations remote from the converter stations. The location of the Ground connection is chosen to avoid corrosion and interference of infrastructure. The Electrode line is energized at much lower voltage than the HVdc line, therefore requiring much smaller towers.

The conversion process creates on the ac side a voltage that requires cleaning,[13] to avoid problems on the ac network. Switchable ac harmonic filters perform this clean up.[14]

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[9] Phone chargers offer an example of a simple power electronic converter, plugging into the home power ac socket to charge the battery in a mobile phone. TV's have inbuilt power electronic converters to provide the dc power for the electronic circuits and the screen. Some HVdc converter stations are capable of handling more than 100 Million times the power provided by a phone charger.

[10] An HVdc line carries the power using dc. A Monopolar HVdc scheme needs only one HVdc conductor, and one Ground connection conductor, which can sometimes be supported on the same transmission tower as the HVdc conductor.

[11] An HVdc OHL line looks similar to a normal High Voltage ac Power transmission line, but uses only one (for a Monopolar system) or two (for a Bipolar system) bundles of High Voltage conductors.

[12] In some HVdc schemes only one converter station is connected directly to a local grounding point, and the other converter station is connected to this point through an insulated conductor (called a metallic return conductor), which is run on the main transmission towers back to the directly grounded station.

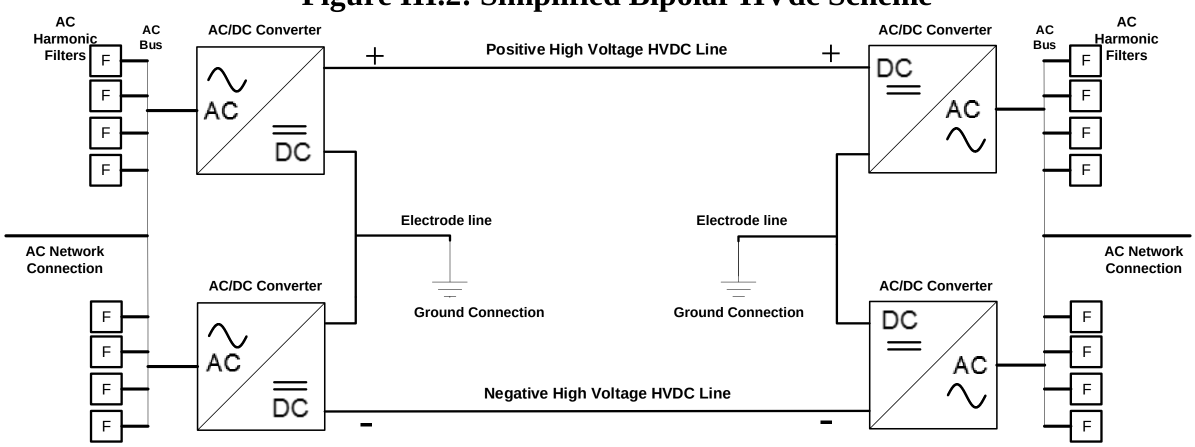
[13] The untreated voltage consists of the smooth fundamental frequency voltage that is used for power delivery, as well as unwanted distortion, which is called harmonics

In a Monopolar scheme, permanent faults in the converters, in the High Voltage HVdc Line, or in the Electrode lines result in the loss of all power transmission capability, until the fault has been repaired. This performance is similar to that of a single circuit[15] ac line.

HVdc schemes are very complex, and have many components that can fail occasionally. These schemes therefore require steps to reduce the number of outages caused by converter faults. Employing two control systems, for example, provides redundancy in that either of the two systems is capable of controlling the converter station. In the event of a fault in one control system, the other instantly takes over control, allowing the scheme to continue in service. The converters include redundancy, so that the failure of individual elements do not result in an outage, with redundancy restored at annual or bi-annual maintenance stoppages. Similarly, redundant ac harmonic filters are typically used, preventing a fault in one ac harmonic filter from causing permanent loss of power transmission capability (because the affected filter will be disconnected by protection).

The transmission of high power or the need to ensure very high reliability of power transmission often results in the use of a Bipolar HVdc scheme, consisting of two power blocks (see Figure III.2).

Figure III.2: Simplified Bipolar HVdc Scheme



A Bipolar HVdc scheme consists of two monopolar schemes connected together. One monopolar scheme operates with a positive voltage (+) (the positive pole) and the other with a negative voltage (-) (the negative pole). The two poles normally operate with the same power, which lessens power loss, because the current in the Electrode line will be very low.[16] The two monopolar schemes are kept as separate from each other as possible (given economic limits), in

[14] The ac harmonic filters reduce the distortion caused by the conversion process.
[15] A single circuit ac line has three main conductors; each conductor being supported from the transmission tower by insulators. The conductors are typically made of aluminum, but copper is typically used for submarine cables.
[16] The power loss is mostly caused by the current flowing in the lines and in the converters. The current flowing in the Electrode line is the difference between the current flowing in the positive conductor and in the negative conductor. The power loss is caused by the resistance of the line and in the converter.

order to make faults in some common equipment the only cause of a loss of all power transmission.

Typically, the common equipment on a bipolar HVdc scheme includes:

- The HVDC OHL towers, if conductors for both poles are carried on the same tower[17]
- The Electrode line
- The Ground connection
- The equipment required to connect the low voltage points of the two converters
- A small part of the control scheme used for co-ordination of the two poles.

The ac busbars for each monopolar scheme are normally kept separate, and, where possible, different connections to the ac network are used.

In a Bipolar HVdc system, the reliability of the power connection can be increased by designing the equipment with significant overload capability. In the event of a fault on one part of the scheme (a pole), the other part/pole can increase its power transmission to compensate as far as possible for the loss of the power transmission on the faulty pole. However, when power transmission on a pole increases, the power loss[18] in the converter and the HVdc line and electrode line will increase substantially. This means that doubling the power injected at the sending end will result in less than double the output at the receiving end.

B. Reliability Criteria

Hydro's reliability criteria and how the criteria are applied are key determinants in the design of the current IIS and also the Muskrat Falls interconnection. Most utilities use the same or similar criteria, but not all apply the criteria in the same way.

Many utilities plan for a single contingency, which is called the N-1 criterion, which means that the design should provide for no loss of load with only one failure. An N-2 criterion, which is seen in highly reliable systems such as urban networks, means the system is designed for no loss of load for any two simultaneous failures. A middle ground is N-1-1 which means that the design provides for no loss of load on a single failure followed sometime later by a second failure. The time delay represents an opportunity for the system operator to configure the system after the first failure.

Hydro uses the N-1 criterion in its reliability planning for the IIS and has also applied it to the design for Muskrat Falls. Hydro defines an N-1 condition as an operating condition where a major transmission asset (e.g. a 230kV or a 138kV transmission line, shunt capacitor banks, synchronous condensers or a transformer) has been lost, either due to maintenance or a fault. No loss of supply to customers should occur in an N-1 event. Any scenario that is beyond N-1 is not designed for by Hydro so that Hydro does not design the system to prevent loss of load under N-2 or N-1-1 conditions.

[17] On some bipolar schemes the conductors for the two poles are carried on separate towers, but the two towers require a wider line corridor and costs significantly more,

[18] When the current in the line doubles, the power loss is quadrupled.

We refer to the application of the N-1 reliability criteria Hydro uses throughout this report and discuss its implications for loss of supply to customers in various scenarios.

C. Overview of LIL

The response to PUB-NLH-221, "LIL Project Description", provides a brief summary of the LIL. Additional information has been provided in other responses to RFIs in the investigation and is referred to when necessary in this report.

The LIL will be a 900 MW Bipolar ±350kVdc High Voltage Direct Current (HVdc) scheme, consisting of two equal parts called poles (each rated at 450 MW). The design of the two poles seeks to keep them as autonomous and separate from each other as economically practical. The converter system (referred to as a Bipole, or as being Bipolar) consists of the two poles (each called a monopole) and the common neutral equipment. When only one pole is in operation, the LIL will be in monopolar operation.

The LIL will include converter stations at Muskrat Falls in Labrador and at Soldiers Pond on the IIS. The converter stations in each pole connect to each other via double circuit HVdc overhead lines from the converter stations to the Strait of Belle Isle. Land and subsea cables provide for the crossing of the Strait. The neutral points of the poles at the two converter stations are connected to an electrode line, which connects the neutral point to a sea-electrode. The two sea electrodes are located at considerable distance from the converter stations.

1. Description of the Muskrat Falls Project Bipolar System

The response to PUB-NLH-246 provides single line diagrams of the converter stations and the dc switching station. The single line diagrams include all of the components expected from a good design of a bipolar HVdc scheme with associated dc cable switching stations. Some subsequent changes have further improved the design, *e.g.,* the use of inrush limiting resistors at the dc cable switching stations.[19]

HVdc OHL and HVdc cables will provide the High Voltage (HV) connection between the converter stations at Muskrat Falls and Soldiers Pond. The neutral points of the converter stations at Muskrat Falls and Soldiers Pond connect to each other through electrode lines and sea electrodes. The arrangement of the LIL (apart from the use of 3 parallel subsea cables), is similar to that used on many other Bipolar HVdc schemes in the world.

A brief description of each of the above elements follows.

a. HVdc OHL

The HVdc OHL will have one HV conductor for the positive voltage pole and one conductor for the negative voltage pole. The same steel lattice towers will carry the conductors, suspended from the tower structure by means of electrical insulators.

[19] PUB-NLH-235

The HV conductors will be protected against direct lightning strikes by means of an Optical Fiber Ground Wire (GW) which is attached to the top of the OHL towers, above the HVdc conductors[20]. The GW does not carry significant current during operation; therefore, it can have a smaller diameter than the main current carrying conductors require.

During some parts of the route, the HVdc OHL will run in the same corridor[21] as other existing ac OHLs. The design of the ac lines and the dc line and the width of the Right of Way (RoW) will provide sufficient air clearance and preclude physical contact between the ac and the dc infrastructures during normal operating conditions.[22]

Hydro has clarified that, in the event of a tower failure, the HVdc OHL has been designed so as not to fall outside the HVdc right of way.[23] This will prevent failure of both the HVdc and HVac lines when run in close proximity to each other.

When ac and dc lines run in close proximity to each other, there is also a risk of adverse fundamental frequency induction[24] from the ac line to the dc line. Such fundamental frequency induction could result in saturation of the converter transformers, causing the converter to inject excessive harmonics into the ac system leading to a trip of the converter station. Hydro has addressed this issue, confirming that the HVdc system contractor will take into account the proximity of the ac and dc lines in design.[25] If necessary, the effect can be mitigated by transposition[26] of the ac lines and/or the introduction of fundamental frequency blocking filters[27] on the dc lines. The early circuit diagram for the converter stations included an optional fundamental frequency blocking dc filter. However, Hydro has confirmed that the Contractor has performed the necessary studies, and has determined that no fundamental frequency blocking filters are required.[28]

Hydro has taken pollution levels and forest fires into account in the design of the insulation of the HVdc OHL.[29] Longer insulator strings will be used in areas subject to higher levels of contamination.

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[20] Note that a lightning strike to the ground wire can under some conditions result in a flashover from one or even both HV conductors to the tower, particularly if the earthing impedance of the tower is large, or if the magnitude of the lightning strike current is very large.
[21] The corridor is a strip of land in which vegetation is managed so that the air clearance is maintained, in order to prevent flashover to ground during normal operating conditions.
[22] PUB-NLH-268 and PUB-NLH-270
[23] PUB-NLH-556
[24] The current in the ac line creates a magnetic field, which in turn is picked up by the HVdc line conductor, resulting in fundamental frequency current flowing on the dc line. If the magnitude of this is low enough it is of no concern, but at high levels significant problems could arise as discussed.
[25] PUB-NLH-269
[26] Transposition is performed by changing the location of the three ac conductors at predetermined locations. This approach minimizes the impact of the magnetic field from the ac line.
[27] The blocking filter is very high impedance at the fundamental frequency, and reduces the induced current flowing into the converter to an acceptable level.
[28] CA-NLH-104
[29] PUB-NLH-516

The converter stations and the HVdc OHL will have considerable overload capability.[30] Each converter pole and the HVdc OHL will be designed to operate at twice the rated current for 10 minutes, after which the current needs to be reduced over the next 10 minutes to 1.5 times the rated current. The pole can continue in service at that level for an indefinite period.

The overload capability minimizes the impact of the trip of a pole, as we discuss later. The scheme has not been designed for operation at power levels higher than the rated power when in bipolar operation. Hydro explained that this approach has been taken primarily because the HVdc cables cannot operate continuously at current levels higher than the rated level.[31]

b. HVdc Cables

Three HVdc cables[32] rated at 450 MW each will be provided at the Strait of Belle Isle crossing. This approach provides one more cable than would be required for the bipolar HVdc scheme. In normal operation all cables will be energized, with two connected to one pole, and the remaining cable to the other pole.

The HVdc cables will employ a mass impregnated design; *i.e.*, a proven technology provided on HVdc schemes for several decades. A 50-year life has been specified for the LIL HVdc cables.[33] Many such HVdc cables have provided reliable operation over the decades.

The HVdc cable manufacturer will have responsibility for the design, delivery and installation of the HVdc cable.[34] The manufacturer is also responsible for the specification of the Horizontal Directional Drilling (HDD) operation[35,36] and the cable mechanical stresses during rock berm installation.[37] This allocation of responsibilities is sound in our opinion, given the risk of damage to the HVdc cable during installation.

The decision to use three cables resulted from recognition that cable failures may occur and that repairs can take significant time (two to eight months) to complete, given sea and ice conditions during the winter months.[38] Data provided in the response by Hydro indicates that it may prove difficult to effect cable repairs outside of the period from June to September.[39] In normal

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[30] Note that overload capability is expressed in terms of current and not power, because the current dictates the (thermal) limit. Power losses increase when the current increases; therefore, the power delivered at the inverter will not double when the current is increased by a factor of 2.
[31] PUB-NLH-550
[32] An HVdc cable consists of a conductor surrounded by insulation material, and then protected against ingress of water and mechanical damage during installation.
[33] DD-NLH-067
[34] PUB-NLH-242
[35] This steerable trenchless method of installing underground pipe, conduit, or cable in a shallow arc along a prescribed bore path uses a surface-launched drilling rig, with minimal impact on the surrounding area.
[36] PUB-NLH-243
[37] PUB-NLH-244
[38] Repairing a failure in a submarine cable occurs by raising the cable from the sea bed to a vessel at the surface. On-board specialists then cut out the damaged section of the cable, and replace it with a new length of cable, which is then lowered to the sea bed, and protected by rock or concrete “mattresses”. This operation can only be done during relatively calm conditions.
[39] DD-NLH-097

operation all cables will be energized, with two connected to one pole, and the remaining cable to the other pole.

Each HVdc cable can operate at twice the rated current for 5 minutes, after which the current needs to be reduced to the normal rated current. This overload capability, however, covers a shorter period than that of the converters and the HVdc OHL. Provision of a longer duration for the overload capability, and/or making the cables capable of continuous operation at 1.5 times the rated current would have increased the cost of the cables substantially.

The limited over-current rating of the cables means that dc cable switching becomes necessary following a trip of the pole with two parallel cables. This configuration makes it necessary to switch the cable from the tripped pole to parallel operation on the remaining pole within 5 minutes. Under-frequency load shedding (UFLS) would otherwise be required for a permanent pole trip. Hydro has confirmed that the cable switching arrangement design meets this requirement.[40]

For some cable configurations, it will be necessary to disconnect one of the two parallel connected cables (to enable it to be transferred to the other pole) before bipolar operation can be resumed. This disconnection would require a brief blocking of the converter (probably less than 200ms), but blocking does not need to occur until the system is stable, and can withstand the brief interruption in power supply. The reason for transferring the cable is primarily to reduce the power loss.[41] Hydro has confirmed that dc cable design and testing will verify the necessary dc voltage reversal capability.[42]

c. Electrode Lines and Sea Electrodes

The low voltage connection, called the neutral, of the two converter poles occurs at the midpoint of the bipolar system. The midpoint does not directly connect to the station ground mat, but connects to sea electrodes through electrode lines. This part of the system will be common to both poles. The midpoints of the two converter stations connect to each other through the electrode lines and the sea electrode through the water and ground. The connection has a very low resistance and impedance.[43]

The connection of the neutrals of the two converter stations through a low resistance and impedance connection enables one pole to stay in service in the event of a problem with the other pole, because the dc current is diverted from the other pole into the neutral connection. This configuration of the HVdc scheme minimizes, but does not completely eliminate, the probability that a single event will cause a trip of the complete transmission link which is discussed later.

The response to PUB-NLH-259 describes the electrode line connections to the sea electrodes. The design employs two parallel conductors, which reduces the risk of the connection to the electrode becoming open circuit. However, the additional conductor will also increase the risk of a ground fault on the electrode line, because the longer the conductor the higher the risk of a

[40] PUB-NLH-282 and PUB-NLH-469
[41] PUB-NLH-470
[42] CA-NLH-106
[43] The impedance of a connection consists of the resistance and the inductance.

conductor failure.[44] A faulted conductor can be switched out of service using switchgear at the converter stations and at the electrode stations.

The individual electrode line conductors will not be sized to permit each to carry the normal full pole current, the continuous overload current of 1.5 pu[45], or the 10 minutes overload current of 2.0 pu. Therefore, during the outage of one electrode line conductor, the electrode line may restrict the power import on the LIL. The design creates the potential need for load shedding in the event of a pole trip.

Furthermore, the electrode line's relatively long length (300 km) and the higher resistance resulting from operation with a single electrode conductor would result in substantially less power being delivered to Soldiers Pond. Hydro considers this scenario to be an N-1-1 failure, and therefore not one for which it has designed.

The maximum power that can be delivered to Soldiers Pond with a single electrode conductor out of service depends on the ambient temperature and the duration. The response to PUB-NLH-468 provides the data shown in the following table.

Table III.3: Maximum Power Delivered to Soldiers Pond with Single Electrode Conductor out of Service

Ambient Temperature °C	Overload Time (min)	Current (A)	Power (MW)	I^2R Power Losses	Power Delivered to SOP (MW)
0	10	1750	612.50	130.12	482.38
	20	1490	521.50	94.33	427.17
	30	1450	507.50	89.33	418.17
	Infinite	1442	504.70	88.35	**416.35**
20	10	1590	556.50	107.42	449.08
	20	1310	458.50	72.92	385.58
	30	1240	434.00	65.33	368.67
	Infinite	1204	421.40	61.59	**359.81**
30	10	1480	518.00	93.07	424.93
	20	1205	421.75	61.70	360.05
	30	1120	392.00	53.30	338.70
	Infinite	1062	371.70	47.92	**323.78**

[44] Electrode line conductor faults may include permanent faults to ground (*e.g.*, because of damage to the insulator that supports the conductor) or open circuit faults (*e.g.*, because crimps used to join conductors or clamps at the insulator fails).
[45] "pu" stands for per unit. The unit normally referred to is the rated value. In this case 1.5 pu means that the current is 1.5 times the rated current.

The power delivered at Soldiers Pond during continuous overload operation at an ambient temperature of 30°C with two electrode line conductors is 530.6 MW; *i.e.*, the power reduction is 206 MW. At 0°C the reduction would be 114.3 MW.

Operation with an electrode line conductor out of service is likely to be a rare event, and the limitation of the power transfer shown in the preceding table applies only to operation in monopolar mode. Load shedding as a consequence of the limitation would occur only to the extent that reduction of power delivery at Soldiers Pond results in a power shortage in the IIS, taking into account the load and generation in service at the time, and the ability to curtail the Maritime Link.

Hydro has acknowledged[46] that, during operation with a single electrode line conductor during the winter peak period, an outage of one pole could result in a power shortfall in the LIL of 58.8 MW after all standby generation has been started and with the Maritime Link providing 300 MW at Bottom Brook converter station.

This scenario was not considered in the design of the conductor, because it was considered a second contingency (N-2) situation.[47] A larger conductor could have been accommodated on the towers, if this requirement had been taken into account in the original design of the transmission line and its structure. Hydro has calculated the return period of the electrode conductor rating limitation resulting in a power shortage as approximately 1600 years, which results in a very small impact on the reliability index.[48]

d. DC Switching Arrangements

The converter stations at Muskrat Falls and at Soldiers Point have the necessary switchgear to enable the switching of electrode line conductors, the electrode line and the HVdc connections.
The dc switching capability enables the HVdc scheme to operate with a connection between the neutral points of the converter stations by means of electrode lines and shore electrodes (used for bipolar or monopolar operation) or the HVdc OHL and HVdc cable used as a metallic return[49] (only possible in monopolar operation).

Regulatory permission is not at present required for monopolar operation with ground return[50] in Newfoundland; several HVdc schemes around the world use this approach. Should regulations change in the future; *e.g.*, to prohibit long term continuous operation with ground return, the dc switchgear can be used to switch from ground return operation to metallic return operation. The converter station dc switchgear is designed to transfer operation between these modes while the HVdc scheme is in operation.[51]

[46] PUB-NLH-504
[47] PUB-NLH-505
[48] PUB-NLH-585
[49] In metallic return operation the neutral point of one converter station is connected directly to ground, and the neutral point of the other converter station is connected to this grounding point through one HVdc OHL and a HVdc cable. No dc current flows into the ground connection.
[50] CA-NLH-102
[51] PUB-NLH-246 and PUB-NLH-442

Metallic return operation results in higher power loss and therefore lower power delivery at Soldiers Pond. However, this mode of operation may be useful during light load conditions, because it will enable the maintenance of the electrode line and the sea electrodes, if required.[52] In metallic return operation the maximum power that can be delivered at Soldiers Pond will be 386 MW (450 MW at Muskrat Falls).

e. DC Switching Stations

The dc switching stations located at the intersection between the HVdc OHL and the dc cables for the Strait of Belle Isle enable the individual dc cables to be connected to either of the HVdc OHLs.

When all cables are available, two will be connected to one pole and one will be connected to the other. If the pole that trips has two cables connected, then one of these cables has to be reconnected to the remaining in-service pole within 5 minutes. Load shedding would otherwise become necessary, because the current has to be quickly reduced to the rated value after 5 minutes.

The dc switching stations have all the switchgear required to transfer the dc cables between the poles.[53] The dc switchgear used for the cable switching operations will be ac circuit breakers equipped with in-rush limiting resistors to minimize the stresses on the cables and the dc switchgear. This is a prudent measure to increase the reliability of the dc switching station.[54]

In the original design, the dc switching stations included a building for the transition between the dc cables and the switchgear, which would have provided a more reliable design.[55] However, during design optimizations the indoor design was abandoned in favor of a less expensive outdoor design. The response to PUB-NLH-509 provided information concerning the outdoor equipment and overall design, which includes allowances for snow, wind and the worst case ambient conditions, including salt contamination. The access to the dc switching station during an extreme weather event would be as for other critical infrastructure, and seems acceptable.

Reliability and forced outage calculations have not included the dc switching station. Clearly, the dc switching station will add additional equipment to the HVdc scheme, bringing the risk of additional failures and outages. However, such outages are likely to be monopolar and of relatively short duration, unless access to the switching station become difficult (*e.g.*, because of extreme weather conditions).

f. Conclusions

III-1. The design of the LIL bipolar system includes the measures expected of a well-designed critical infrastructure project.

Such measures include:

[52] PUB-NLH-558
[53] PUB-NLH-246
[54] PUB-NLH-235, 282 and 470
[55] PUB-NLH-588

- Redundancy in subsystems and components, where economically possible.
- Large overload capability of the poles to minimize the impact of pole failure.
- The provision of three dc cables rather than the minimum two, to give higher resilience in case of the failure of one cable, the repair of which could take several months.
- A dc switching station to enable re-configuration of the dc cables.

These measures increase the flexibility of the HVdc scheme, and maximize the power delivery capacity in the event of a fault on individual system components.

The dc switching station provides additional flexibility to the bipolar scheme, enabling the 3 HVdc cables to be switched as necessary to meet the over-current requirements during monopolar operation with 1.5 times the rated dc current. The dc switching stations are likely to result in higher scheme availability, compared with the option of two directly connected HVdc cables, despite the need for additional equipment.

III-2. One weakness of the LIL bipole design is the lower rating of the electrode line conductors, as compared with the HV conductors.

The lower rating will reduce the power that can be delivered at Soldiers Pond when only one of the electrode line conductors is in service in monopolar operation. The reduction will depend on the ambient temperature. The reduction during the high load periods in the winter months could result in a power short fall on the IIS of 58.8 MW. Nevertheless, the return period for this event has been calculated as 1,600 years, so it will have negligible impact on overall reliability.

2. Description of the Poles

a. Findings

Each of the 450 MW poles has a converter at each end; one converts ac power to dc power[56] (normally at Muskrat Falls) and the other converts dc power back to ac power[57] (normally at Soldiers Pond). The converter uses large diameter controlled thyristors for the conversion process, and relies on the ac system voltage having a reasonably good waveform for its correct function. The converter is a line commutated converter (LCC).[58]

To improve the ac voltage waveform, ac harmonic filters will deal with harmonic current produced by the conversion process. The ac harmonic filters are customized to the network to which they are connected; *i.e.*, they are different at the two ends. The ac harmonic filters also provide reactive power,[59] and offsets some or all of the reactive power absorbed by the

[56] Called the rectifier
[57] Called the inverter
[58] There are now two different HVdc converter types. The LCC relies on the ac voltage for correct operation. The newer voltage source converter scheme (VSC), used on the Maritime Link, is self-commutating, which means that it can operate into a network without any generation.
[59] There are two different kinds of ac power. There is Real Power (sometime called Active Power), which results from loads, such as heating loads and motors, and is calculated as the multiplication of the Voltage and the Current component in phase with the Voltage. Reactive Power results from current flow in reactors and capacitors, and is calculated as the multiplication of the Voltage and the Current component in quadrature (i.e. offset by 90° electrical) to the Voltage. The reactive power has an impact on the ac voltage amplitude.

converters during the conversion process. The ac harmonic filters are switched in and out as the power being transmitted changes, with the objective of controlling the power factor[60] of the converter to near unity.

While the ac harmonic filters for the two poles are connected into different points in the ac switchyard, the two sets of filters can be used for either pole. This is important, because the filters are essential for the support of the ac voltage during the trip of a pole (as discussed below), because the pole in overload operation (see below) will absorb much more reactive power than normal.

The Muskrat Falls converter station has a total of 5 harmonic filters and the Soldiers Pond converter station has a total of 6 harmonic filters.[61] One harmonic filter is a spare at each converter station; *i.e.*, it is not required for normal operation. With one filter out of service, there could be a shortfall of reactive power during a pole trip, particularly during the period when the remaining pole operates at 100% overload. Unless this reactive power can be provided from other sources (*e.g.,* the synchronous condensers at Soldiers Pond), the lack of reactive power could result in reduced ac voltage, and potentially limit the power transmission capability. Hydro has confirmed that all studies done to date have assumed that the spare ac harmonic filters are not in service.[62] Therefore, it appears that sufficient reactive power support exists at both stations.

The converters will be designed to be capable of quickly increasing the direct current to twice the normal rated current (100% direct current overload) for a period of 10 minutes. The capability to increase the direct current will be used in the event of a permanent fault resulting in a trip of the other pole. When a pole trip is detected, the other pole will immediately be ordered to pick up as much as possible of the power shortage caused by the trip of the other pole.

When the direct current is increased, the power loss in the converter, HVdc OHL and HVdc cable will increase substantially.[63] The following table illustrates this result, showing the power delivery at Soldiers Pond for different operating conditions.

[60] The power factor is a measure of the phase angle between the ac voltage and the ac current. When the two are perfectly in phase the power factor is 1. When the two are in quadrature, the power factor is 0. For an HVdc scheme the power factor is typically higher than 0.95
[61] PUB-NLH-552
[62] PUB-NLH-506
[63] The power loss is a function of the square of the current in resistive components, i.e. doubling the current results in the power loss in resistive components being multiplied by 4. Some of the power loss components are not resistive, e.g. the power semiconductors have a large fixed voltage drop, and this part of the power loss would increase linearly.

Table III.4: Power Delivered to Soldiers Pond

Configuration of LIL	Power Taken from Muskrat Falls Converter Station	Power Injected to the ac System at Soldiers Pond
Bipole – rated power	900 MW	807.9 MW
Monopole – 100% overload	900 MW	627.2 MW
Monopole – 50% overload	675 MW	530.6 MW

The power delivered at Soldiers Pond when in monopolar operation is based on two electrode line conductors being in service. When only one electrode line conductor is in service, the power delivered will be lower as described in the section on Electrode Lines and Sea Electrodes above.

The 10-minute period with 100% direct current overload is beneficial in that it may allow standby generation in the IIS to be started, and therefore minimize or avoid the need for load shedding. Following the 10-minute period, the direct current has to be gradually reduced over the next 10-minutes to 1.5 times the normal rated current. The pole can then continue to operate at this level as long as required.

Hydro states that the required additional generation can be started and ramped up to match the ramping down of the LIL over the 10-minute period. The availability of this capability of the converters and the standby generation is confirmed in the response to PUB-NLH-496. The HVdc overhead line and the two parallel electrode line conductors will have the same overload capability as the converters.

Three dc cables will be provided, with each rated for 450 MW at Muskrat Falls (MF) monopolar operation (*i.e.*, one cable is spare). Each HVdc cable has a direct current overload capability of twice the rated current for 5 minutes only. The dc cables have no continuous overload capability.[64]

The converters will also be capable of working continuously with a reduced dc voltage of ±280kVdc.[65,66] The reduced dc voltage operating mode could prove useful during periods of high pollution, forest fires, icing, or other conditions that might increase the risk of flashovers on one (or both) of the poles.

The reduced dc voltage operating mode will reduce the maximum power delivery at Soldiers Pond during bipolar operation to a value currently estimated as 650 MW,[67] with the actual rating to be determined by the manufacturer during the contract design studies. The power delivered at Soldiers Pond will be shared with the Maritime Link, leaving 527 MW for island use. Hydro has stated that under the reduced dc voltage scenario there is sufficient island generating capacity until the 2030s. [68,69]

[64] PUB-NLH-221, 282
[65] PUB-NLH-438
[66] Operation at reduced voltage has no impact on the HVdc OHL or the dc cables or the electrode lines.
[67] PUB-NLH-439
[68] PUB-NLH-439
[69] Liberty does not believe this is an accurate assumption, as discussed in detail later in Chapter IV, Power Supply.

Using the same power reduction (80%) for the maximum power delivery in monopolar operation (i.e. during a pole outage), the maximum power delivery at Soldiers Pond would be reduced to 424 MW. It is assumed that under these operating conditions and circumstances it would not be necessary to share this power with the Maritime Link. Nevertheless, mono-polar operation at reduced voltage during bad weather at winter peak periods may be a credible scenario, and unless island generation is available to pick up the reduction in power import (527 MW – 424 MW=103 MW), UFLS could be required.

b. Conclusions

III-3. The poles have been designed with overload capability, which minimizes the impact of the reduction in power delivery at Soldiers Pond in the event of a failure of one pole or a major element within a pole.

However, while the poles have 100% over current capability for 10 minutes, the power delivery capability at Soldiers Pond reduces from 807.9 MW (in bipolar operation) to 627.8 MW in monopolar operation with 900 MW delivered at MF in both cases. Following the 10-minute period of operation at 100% over current, the power delivery capability at Soldiers Pond will be reduced over the next 10 minutes to 530.6 MW, with 675 MW being delivered at Muskrat Falls. To avoid load shedding in the IIS during a trip of one pole when the load in the IIS is high, it may be necessary to curtail the Maritime Link, and then to start standby generation in the IIS and/or to import power from Nova Scotia on the Maritime Link.

The power losses in the electrode line will further reduce the power delivered at Soldiers Pond if only one electrode line conductor is in service, but as mentioned above, this is estimated to be a very low probability occurrence.

III-4. It may be necessary to operate the dc scheme with reduced dc voltage during bad weather conditions, damage to insulators, or forest fires.

The LIL can operate at reduced dc voltage, which makes the LIL more robust. However, this mode of operation results in lower power transmission capability. In bipolar operation, the power delivered at Soldiers Pond for IIS use is reduced to 527 MW which is sufficient, according to Hydro, to avoid a power shortage on the IIS until mid-2030.[70] However, in the event of a permanent pole trip during these conditions, the power delivered at Soldiers Pond by the remaining pole would reduce to an estimated 424 MW, without any allowance for power being delivered to Nova Scotia. This further reduction of about 100 MW could result in a power shortfall on the IIS much earlier than 2030, depending on whether operation with reduced dc voltage may be necessary during periods with high loads.

Hydro considers these circumstances to be an N-1-1condition, for which it does not design.

[70] PUB-NLH-439

3. Maintenance and Technical Support of the LIL

Hydro described the plans concerning annual technical support and service agreements for the converter stations and HVdc cables in the response to CA-NLH-048. The operations team will develop the asset management plans.

The converter station provider will provide annual technical support. It is good practice to enlist the services of the equipment contractors, which can expedite fault finding for non-routine issues, and will ensure equipment maintenance as required, thereby enhancing equipment reliability and availability.

Hydro has significant experience in the building, operation and maintenance of overhead lines; therefore, a service and technical support agreement is not required for this element.

Hydro plans for a support agreement with the HVdc cable manufacturer. The recovery and repair of an HVdc submarine cable requires specialist knowledge to ensure that the dc cable will offer reliable service after the repair. The support agreement with the HVdc submarine cable provider will minimize the risks of further cable damage during the repair and re-burial in the event of a failure of one or more HVdc cables.

D. Inertial Support in the IIS Network

1. Maintenance and Technical Support of the LIL

The LIL will be supported in the IIS by high inertia synchronous condensers.[71] The role of the condensers is to slow down the rate at which the system frequency will drop in the event of a temporary fault/power interruption on the HVdc scheme. The synchronous condensers also provide ac system voltage control through the provision and absorption of reactive power.

The ratings and inertia of the synchronous condensers have been determined based on the need to avoid under-frequency load shedding during a number of different scenarios. The most significant events are likely to be the permanent loss of one pole and a temporary LIL bipole outage; *i.e.*, a lightning strike to the HVdc OHL, which will immediately stop the injection of power into the IIS, until the automatic HVdc control and protection system has cleared the fault and restarted power flow.

During a bipolar trip (the complete loss of import of power from Muskrat Falls) the inertia of the high inertia synchronous condensers will prevent a complete system collapse of the IIS, but will not prevent UFLS.

The response to PUB-NLH-271 identifies the provision of synchronous condensers as follows:

[71] A synchronous condenser is a rotating machine, which can operate both as a motor (when it is being run up to speed) and as a generator (when it slows down). When the system frequency falls, the machine will slow down to remain synchronized with the ac network. By doing so it will the release the reduction in kinetic energy as power delivered to the ac system. The kinetic energy stored in the synchronous condenser depends on the rotating mass and the square of the rotation speed. By increasing the rotating mass, high inertia machines are created, with the capability to deliver more energy to the ac network, thereby slowing the decrease of the ac network frequency.

- Three 175 MVAR high inertia synchronous condensers at Soldiers Pond,
- Holyrood Unit 3 operating as a synchronous condenser, and
- Another nominal 120 MVAR synchronous condenser.

A number of studies have been carried out for many different fault scenarios. These studies have shown that two high inertia 175Mvar synchronous condensers and two other synchronous condensers must be in service when LIL is operated at high power.[72] The provision of three high inertia synchronous condensers allows for one to be out of service for maintenance or repair, both of which activities can require relatively lengthy outages (weeks or months). Scheduled maintenance of the synchronous condensers will normally occur during low load periods[73] of the island system.

Hydro anticipates that all synchronous condensers will be in service during the daily peaks in the winter peak load season. In order to minimize power losses, one synchronous condenser will be removed from service, leaving two in service, when the system loading reduces.[74]

The time to start up a synchronous condenser is 15 minutes.[75] During the 15-minute period after the trip of a synchronous condenser, the IIS would be vulnerable to under-frequency load shedding should another major system event happen, e.g. a temporary bipole block (*e.g.*, due to a lightning strike) or a permanent trip of one of the poles of LIL. Such a scenario would be classified as N-1-1, for which Hydro has not designed.

Another scenario that could result in the need for more inertia to avoid UFLS would be a re-strike on the HVdc line (another flashover to ground immediately after re-energization after a fault clearance). Studies of such events have not yet been performed, but will be performed by the HVdc converter station contractor, using detailed models of the LIL scheme, and with the IIS system fully represented.[76]

Temporary faults on the HVdc system (a temporary power interruption of less than about 1 second) do not show up in the reliability records collected by Cigre.[77] The number of temporary faults will depend on the number of lightning strikes hitting the overhead line and causing a flashover from the conductor to ground. Hydro has not provided information concerning the likely number of lightning strikes that may hit the LIL HVdc OHL, and cause a flashover from one or both conductors to ground. Given that the OHL is very long, the yearly number could be high.

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[72] PUB-NLH-271, 272 and 443
[73] Low loads typically occur in the IIS during the summer months. The power drawn from the synchronous condensers depends on the unbalance between the loads and the combination of IIS generation and power delivered to the IIS on LIL. When the system load is low, less power would be imported by LIL, and therefore in the event of a power interruption on LIL less power would be drawn from the synchronous condensers.
[74] PUB-NLH-271
[75] PUB-NLH-272
[76] PUB-NLH-568
[77] Founded in 1921, CIGRE, the Council on Large Electric Systems, is an international non-profit Association for promoting collaboration with experts from all around the world by sharing knowledge and joining forces to improve electric power systems of today and tomorrow.

The HVdc converter station contractor's studies will either confirm the number and rating of the presently proposed synchronous condensers, or will determine the requirements for additional synchronous condensers. They will also provide an important input to Hydro's operating procedures, and will require careful review in respect of the security of supply to the IIS.

2. Conclusions

III-5. The provision of proposed synchronous condensers appears to be adequate, provided that the models used are realistic and the recovery of the power transmission can be achieved in the time assumed by the simulation models.

The inertia of the IIS is a critical factor in the operation of the system, because the power infeed to the IIS from the LIL will be temporarily interrupted in the event of lightning strikes to the LIL overhead line or permanent faults in one of the LIL poles. The synchronous condensers will supply power to the IIS as the frequency reduces, releasing some of their inertial energy in the process. By doing so, the rate at which the frequency falls is reduced, delaying the time when UFLS will be triggered.

III-6. Hydro has not yet studied re-strikes on the HVdc OHL, which would effectively double or possibly treble the duration for which power flow on one or both poles of the LIL stops.

The HVdc converter station contractor's studies will include restrikes on the HVdc OHL, and may either confirm the number and rating of the presently proposed synchronous condensers, or will determine the requirements for additional synchronous condensers. These studies will also provide an important input to Hydro's operating procedures, and will require careful review in respect of the security of supply to the IIS.

Should the studies show that more synchronous condensers are required than presently planned, they could be added after the LIL enters service. This deferral is possible because the loading on the LIL is not currently planned to be high in the early years of operation.

III-7. Examination of events on the IIS will provide valuable information, and a potential insight into the future performance of the IIS, as the load and power flow increases.

E. The Maritime Link

1. Findings

In addition to the LIL, another HVdc scheme, called the Maritime Link, will be built by Emera to connect Nova Scotia and the IIS. The Maritime Link, which is being built by ABB Sweden, will be a 500 MW Bipolar HVdc scheme using Voltage Source Converter (VSC) technology.

It is understood that the Maritime Link will typically serve to export power from the IIS to Nova Scotia. Emera has the right to part of the energy produced by the Muskrat Falls generating plant. Emera will be able to purchase additional power for export to Nova Scotia, subject to availability. Notwithstanding that the main purpose of the Maritime Link is to export power to Nova Scotia, it will be capable of operating both in the export mode and in the import mode.

LIL is a very large power input and the Maritime Link is a large power load to the IIS. Potentially, the Maritime Link will be able to provide support to the IIS, *e.g.*, in the event of a trip of part or all of the LIL. On the other hand, in principle, interactions between the two HVdc schemes could cause significant problems for the IIS.

The connection point of the Maritime Link in the IIS will be at Bottom Brook substation, which is electrically remote from Soldiers Pond. This configuration reduces the potential for adverse interactions between Maritime Link and LIL. Nevertheless, the absence of adverse interactions needs to be confirmed by the performance of specific interaction studies. Such studies are planned as part of the LIL and Maritime Link contracts.[78]

These studies require the two converter station manufacturers to exchange models of their HVdc schemes. In order to protect the Intellectual Properties Information of the two contractors, so-called black models[79] will be exchanged. The process of exchanging the PSS/E[80] models has been completed.[81] The process for the PSCAD[82] models has commenced, but each party needs to test the other party's model, to ensure that the models are usable in this overall model. This process takes significant time. Both manufacturers will perform studies with these models to enable any adverse interactions to be identified before the two schemes are both in service.

When the Maritime Link models have been accepted by the LIL contractor and the LIL models have been accepted by the Maritime Link contractor, the models will be passed to Hydro and Emera for their use.[83] It is estimated that this process for the more detailed PSCAD converter model will be complete Q2 2016.

The response to PUB-NLH-220, Attachment 3 provides the July 31st, 2012 "Nalcor and Emera Inc. Energy and Capacity Agreement". This agreement describes the conditions under which Hydro would be entitled to curtail the delivery of firm power to Emera, which includes not only the complete loss of the LIL; *i.e.*, a permanent Bipole trip, but also the loss of a pole and other significant losses of transmission lines and equipment in the IIS. The arrangement with the Maritime Link offers significant benefit to the IIS system, as discussed later.

[78] CA-NLH-069
[79] A "black model" is one that provides the correct functional performance of the HVdc scheme, but which is compiled in such a way that the individual components and control and protection algorithms are not visible to the user, and cannot be extracted from the model.
[80] PSS/E is a study program that is used to determine the performance of large ac networks. HVdc schemes can be represented in these studies as average models, which is adequate for the timescales associated with ac networks
[81] CA-NLH-110
[82] PSCAD is a program that is used to study the detailed performance of HVdc schemes. A PSCAD model includes a complete representation of the converter switching elements and passive components. The HVdc control and protection is also included in the model. A simplified representation of the ac network is used for practical reasons, as the focus of the PSCAD studies is the performance of the HVdc scheme, and not the ac network. The PSS/E model of the HVdc control scheme is "tuned" according to the performance achieved using the PSCAD studies.
[83] PUB-NLH-510

The issue of Emergency Power Support is described in the response to PUB-NLH-220 Attachment 7- "Interconnection Operator Agreement". Article 5 deals with emergency support and sharing of spinning reserve between the IIS and Nova Scotia:

> *To the extent practical in accordance with Good Utility Practice and all applicable Reliability Standards, each Party shall exercise due diligence to mitigate an Emergency occurring on its respective Transmission System that affects the Interconnection Facilities. Without limiting the foregoing, where appropriate, each Party shall strive to implement commercial transactions to assist in mitigating such Emergency as soon as possible.*

Hydro has confirmed that no penalties would be incurred by Hydro when the ML is curtailed for issues with the LIL.[84]

Curtailment of the Maritime Link requires direct and fast communication between the LIL and the Maritime Link. A redundant fiber-optic communication channel will be built between the LIL and Maritime Link control systems, to enable high speed commands to be sent from the LIL to the Maritime Link. The communication link and associated controls will need to be designed for high security and reliability, to ensure that no inadvertent trips of either scheme will occur. Hydro's response to NP-NLH-035 provides further information concerning curtailment of the Maritime Link in the event of any supply shortage on the IIS.

Many of the responses to Requests for Information (RFIs) (*e.g.,* PUB-NLH-214, 217, 218, 219, 222, 223, 443, 444, 449, 476, 497) make reference to the curtailment of the Maritime Link in case of a temporary or permanent loss of a pole, a temporary bipole interruption or major incidents in the ac networks.

Hydro has clarified curtailment of the Maritime Link as follows:[85]

> *The curtailment of the Maritime Link (ML) to 0 MW for contingencies on the Labrador – Island HVdc Link (LIL) will result in the ML being instantaneously reduced to 0 MW with the Bottom Brook converter moving to STATCOM[86] mode to provide reactive support and voltage control to the western portion of the Island Interconnected System.*

This means that the curtailment makes the Maritime Link behave not only as an interruptible load, but after reducing the load, it will provide voltage support to the IIS, which may be of considerable benefit.

The benefit of curtailment of the Maritime Link has been demonstrated by studies performed including "ML, Preliminary Interconnection Study" dated August 2014. The response to PUB-NLH-263 summarizes the results of this study. Curtailment (interruption) or run back[87] of the

[84] PUB-NLH-478
[85] PUB-NLH-571
[86] A STATCOM is a reactive power control device, capable of controlling the ac voltage by absorbing or injecting reactive power. It is similar to a Static Var Compensator (SVC), but uses a Voltages Source Converter.
[87] A run back is a pre-set change to the level of power transmission, which will be triggered by an external signal.

power flow on the Maritime Link is used to avoid system collapse or load shedding on the IIS for the following conditions:

- Temporary and permanent pole faults on the LIL;
- Temporary bipole faults on the LIL;
- Outage to 230 kV transmission lines West of Bay d'Espoir;
- Three phase faults on 230 kV transmission lines West of Bay d'Espoir.

In the report the results are summarized as the next table shows.

Table III.5: Summary of Transient Stability Analysis

Contingency	Required Remedial Action
Faults at Bay d'Espoir	No Action Accepted as "Exceptional Contingency"
Faults at Bottom Brook, Buchans, Granite Canal, Massey Drive, Stony Brook, and Upper Salmon	Curtailment of ML Export to 250 MW.
LIL Temporary Bipole Faults	Curtailment of ML Export to 250 MW.
LIL Permanent Pole Faults	Curtailment of ML Export to 250 MW or 0 MW[88].
LIL Faults While in Monopole Mode	Curtailment of ML Export to 0 MW.
Loss of Island Generation	Curtailment of ML Export to 250 MW or 0 MW[89].
Loss of a Synchronous Condenser at Soldiers Pond	Development of Operating Instruction to avoid unacceptable system condition.

Any power on the Maritime Link in excess of 250 MW is not Firm Power.[90]

The curtailment of the Maritime Link reduces the load in the IIS. Accordingly, the ac frequency will reduce more slowly,[91] and therefore less inertia in the IIS is acceptable. In the response to PUB-NLH-445, Hydro has stated that the present analysis of requirements for inertia in the IIS when operating the LIL at rated power indicates that:

i. *When the Maritime Link <u>is in operation</u>, a minimum of two high inertia synchronous condensers at Soldiers Pond plus Holyrood Unit 3 operating in*

[88] Depending on initial value of ML Export
[89] Depending on initial value of ML Export
[90] Firm power is as secure as possible. It is sometimes said to be guaranteed, which means that penalties are associated with its interruption
[91] When there is higher load than is being generated, the generators and the synchronous condensers will start to slow down. As they do so they release inertial energy.

synchronous condenser mode and a nominal 120 MVAR synchronous condenser in the Holyrood/Soldiers Pond area.

ii. *When the Maritime Link* *__is not in operation__* *and the Labrador – Island HVdc Link is operating at full import capability, three high inertia synchronous condensers at Soldiers Pond plus Holyrood Unit 3 operating in synchronous condenser mode and a nominal 120 MVAR synchronous condenser in the Holyrood/Soldiers Pond area are required to minimize the potential for under frequency load shedding on the Island.*

The requirement for less inertia when the Maritime Link is in service shows the benefit to the IIS of the ability to curtail the Maritime Link.

When the IIS system has been stabilized, the power imported to the IIS on the LIL has to be shared on a pro-rata basis between the Nova Scotia Block and the requirements of the IIS with any shortfall for the IIS having to be met by other generation sources on the IIS. Given a continuous monopolar rating of 552 MW at Soldiers Pond, the pro rata split will be 104 MW for the Nova Scotia Block and 448 MW for the Island.[92] This split will have to be taken into account when considering the minimum generation capacity that should be available in the IIS. In the event of a curtailment or reduction in delivery capacity, the energy not transferred will have to be supplied at an agreed later time.

2. Conclusions

III-8. The benefits of the ability to curtail the Maritime Link in the event of problems with the LIL or in the ac network have been shown by studies to be considerable, in terms of the requirements for inertia and spinning reserve.

This result is not surprising, because the Maritime Link will provide a rapidly interruptible load, which makes the IIS more robust and minimizes the spinning reserve and inertia required within the IIS. The introduction of the Maritime Link is likely to improve the power supply reliability in the IIS.

The reliability and availability of the Maritime Link is likely to be similar to that of the LIL, and therefore the Maritime Link cannot be expected to be in service at all times, or to have two poles in service at all times. Taking into account the scheduled hours for delivery of the Muskrat Falls power block to Nova Scotia, the likelihood of the Maritime Link being in service at all times becomes smaller.

3. Recommendations

Recommendation III-1. Hydro should consider the possible need for operation at reduced dc voltage in its planning of IIS standby power generation.

Recommendation III-2. Frequency excursions resulting from all major disturbances in the IIS and in the LIL should be recorded and analyzed, with the event being compared with a study to be performed by Hydro using detailed models of the LIL and the exact network

[92] PUB-NLH-294

configuration and LIL parameters (power and control settings), to identify discrepancies in the actual performance compared with the modeled system.

Should these studies show that the inertial support could become inadequate when the LIL import power increases (*i.e*., that more under-frequency load shedding may be necessary than expected), then plans should be made to install additional synchronous condensers as soon as possible

Recommendation III-3. Studies of the performance of the IIS should be performed not only with the Maritime Link in service, but also with it out of service.

The objective of the studies with the Maritime Link out of service should be to identify operational restrictions for the LIL or the need for additional high inertia synchronous generators.

IV. Reliability of Muskrat Falls

A. Component Reliability and Availability

A complex and large infra-structure project such as an HVdc scheme makes outages due to equipment failures and other causes inevitable. One or both poles of the HVdc scheme will at some time trip unexpectedly. Temporary HVdc scheme faults, typically caused by a flashover to ground from one or both HVdc OHL conductors because of lightning or pollution, will not affect the reliability and availability of the HVdc scheme, unless automatic clearance and recovery from the fault does not work correctly, and the fault becomes permanent; *i.e.*, a trip.

The performance of the ac network, and therefore the HVdc scheme, does depend on other system elements, such as synchronous condensers and ac network protection. The performance of the HVdc scheme depends on the ac voltage and frequency remaining within the specified range. Outages of the HVdc scheme caused by events in the ac network and resulting in ac voltage and frequency deviations outside the specified range are not usually included in the reliability and availability of the HVdc scheme.

This section deals with unexpected trips of the LIL due to equipment failures or events within the LIL. It provides the definitions of the different outages, and then discusses outages in the different components of the LIL and ac network. Hydro has provided information regarding the reliability of the LlL in a number of different documents and responses to RFIs which have been included as references below.[93,94]

In addition to faults within the LIL, outages may result from problems at Muskrat Falls or in the IIS, operator errors, and long term outages of critical transmission lines and system infrastructure, such as synchronous condensers. Such outages will be outlined, but not quantified in this part.

Forecasting the reliability and availability performance of an HVdc scheme can only be performed statistically. The calculations performed by manufacturers typically apply past experience, which is continuously reviewed. The manufacturers learn from their experience, which improves reliability and availability of future schemes using the same technology and building blocks.

1. Definitions

a. Bipole Outages

Cigre defines a bipolar outage as an event that results in the trip of both poles and therefore the sudden loss of all power transfer capability on a scheme operating in bipolar operation. This event comprises the most serious fault for a bipolar HVdc scheme; it will stop all power transmission on the HVdc scheme. With a bipolar outage, there is no warning and therefore no

[93] Reliability & Availability of the HVdc Island Link, SNC-Lavalin, 10 Apr-2012, PUB-NLH 212, Attachment 2
[94] Labrador-Island HVDC Link and Island Interconnected System reliability, October 30, 2011, Hydro System Planning Department.

time for the operator to make the ac network more robust in dealing with the consequences of the cessation of power transmission.

Following a bipolar outage, the operator will typically:

- Initiate fault investigation and repair
- Investigate the possibility of returning at least one pole to service
- Start available offline power generation and re-instate as much load as possible.

b. Monopolar Outages

Cigre defines a monopolar outage as an event that results in the trip of one pole of an HVdc scheme. Following a monopolar outage, the operator will typically do two things:

- Initiate fault investigation and repair
- Take all available steps to make the ac network as robust and resistant as possible, in case a further pole fault happens.

c. Temporary Interruption

A temporary interruption consists of an event that does not result in the tripping of the converter ac breakers, but involves a power transmission interruption for a period typically less than 500ms.

2. Impact of Outages

a. Bipolar Outages

If both poles trip, all power transmission from Muskrat Falls to the IIS will stop immediately. Unless the load on the LIL is low and can be picked up by on island generation or can be dropped (*e.g.,* interruptible loads), UFLS will become necessary in order to avoid a total collapse of the IIS. In the event of an LIL bipolar trip, any export on the Maritime Link will be curtailed, thereby reducing the IIS load. Even so, unless the power import on the LIL is very low, UFLS will likely prove necessary to prevent total system collapse.

In the worst case (i.e., maximum import to the IIS of 830 MW delivered to Soldiers Pond and 157 MW exported by the Maritime Link), immediate UFLS of 673 MW in the IIS could become necessary.[95] Starting available standby generation could reduce this amount to 516.8 MW after about 20 minutes, and then to 396.8 MW after 40 minutes.[96]

Experience from other bipolar HVdc systems shows that most modern HVdc schemes do not experience bipole trips (simultaneous loss of both poles) very frequently -- only every few years.

b. Monopolar Outages

When operating in bipolar mode, use of the overload capability of the HVdc scheme can mitigate the impact of a pole trip. In the event of a pole trip, exports on the Maritime Link can,

[95] PUB-NLH-217
[96] GRK-NLH-136

if necessary, be curtailed, thereby reducing the IIS load. Statistics indicate many monopolar outages can occur each year on a bipolar scheme.

c. Temporary Interruption

Temporary interruption or reduction of the delivery on the LIL of power from Muskrat Falls to Soldiers Pond can result from:

- Temporary faults in the ac network close to Muskrat Falls
- Flashover to ground from one (a monopolar fault) or both (a bipolar fault) of the HVdc OHL conductors, from causes such as lightning strikes or weakening of the air insulation (e.g., due to causes like salt fog pollution or forest fires)
- Temporary faults in the ac network close to Soldiers Pond.

Temporary faults usually have no consequence to the ac network. However, two features of the LIL require detailed study of potential consequences:

- The LIL's connection to the relatively small IIS
- A rating much higher than any of the generators in the ac network.

Hydro has performed a number of studies which have shown the necessity for adding synchronous condensers with high inertia and high reactive power rating and curtailment of the Maritime Link to prevent temporary interruptions that might require load shedding for the ac network (see section IV.B below).

3. Converter Station Reliability

a. Bipolar Trips

Events in the converter station that could cause a bipolar trip[97] include:

- Some control and protection failures or mal-operation
- Operator error
- Fault to ground in the neutral area of the HVdc scheme
- Fire in the control equipment room

Hydro also considers the trip of the remaining pole under monopolar operation (*e.g.*, because the other pole has been taken out of service by a trip or for maintenance) to comprise a bipolar trip and hence an N-2 event which is not included in its design or planning criteria. Hydro therefore considers the resulting possibility of UFLS to be acceptable.

b. Pole Trips

Events in the converter station that could cause a pole trip include:

- Control and protection failures
- Converter[98] equipment failure
- Fire in the valve hall or equipment rooms

[97] A bipole trip occurs upon the opening of the ac circuit breakers on both of the poles forming the bipole.
[98] The converter includes, for the purpose of this discussion, all of the equipment from the ac breaker to the HVdc OHL connection.

- Operator error
- Fault to ground within the converter area
- AC bus failures to ground

A fault in an ac harmonic filter will not normally result in a trip of the pole. However, if sufficient other sources of reactive power support (*e.g.*, synchronous condensers) are not available, a filter trip could reduce the power capability of the bipole, or of the pole, particularly when attempting to operate at 100% overload.[99]

c. Predicted Performance of Converter Stations

Hydro has provided information concerning reliability and availability of the converter stations in PUB-NLH-212, Attachment 1 and Attachment 2. The information relies on data provided by a Cigre survey of performance of HVdc schemes throughout the world for the period 2007 to 2008, as well as an average for the years 1998 to 2008.

Not all HVdc schemes report their performance to Cigre, but the Cigre information nevertheless remains valuable. The Cigre data provided biannually covers primarily the performance of the HVdc converter stations, including limited information about the HVdc OHL and HVdc cables.

The Cigre data for 2007 to 2008, for a bipolar scheme similar to the LIL, gives an average range of 0.76 to 9.8 pole outages per year, excluding outages caused by the HVdc OHL or HVdc cables. The duration of the pole outages ranges from 2.6 to 484.2 hours. The data in PUB-NLH-212 Attachment 2, section 2.1, based on an average over 1998 to 2008, is slightly different, indicating 4 pole outages/year and an average of 21 hours per outage.

As mentioned above, the LIL design provides overload capability of the poles, therefore making it likely that a pole failure will have a relatively small impact on the power supply to the IIS (unless the starting point is already an N-1 condition). An N-1 condition could result from causes such as the outage of one pole, two or more ac harmonic filters out of service, operation with a single electrode line conductor, or two or more high-inertia synchronous condensers out of service, for example.

The 2007 to 2008 Cigre data for bipole outages gives, for a bipolar scheme similar to the LIL, an average range of 0 to 0.42 bipole outages per year, excluding outages caused by the OHL or HVdc cables. The average duration of the bipole outages ranges from 1.03 to 2.27 hours. The data in PUB-NLH-212 Attachment 2 section 2.1, based on an average over 1998 to 2008, is slightly different with 0.4 bipole outages/year and 1.3 hours per outage. The low average outage time indicates that switching operations undertaken by well trained and experienced operators resolve a number of the outages.

Hydro states that the LIL can be restored to service within 3 hours of a bipole fault caused by a converter station issue. Such fast repair time will require an experienced fault finding and

[99] If insufficient reactive power supply is available near to the converter station, the high reactive power absorption during 100% overload operation could result in a significant reduction in the ac voltage amplitude, which can only be corrected by a reduction of the dc power transmission level.

repair/maintenance staff able to attend the converter station very quickly/immediately after the fault, and available, adequate spares for all components. Major faults, such as a breakdown of equipment in the neutral area (surge arresters, switches, capacitors, for example), take longer than minor faults (*e.g.*, operator errors), because of the need to identify and remove the failed equipment and recommission replacements.

A bipole fault occurring when the LIL is operating at high load will make extensive UFLS likely. It may prove possible to restore some customers relatively quickly, but restoration of power to all consumers may take some time.

d. Guaranteed Performance of the Converter Stations

Guaranteed performance is important because of its association with penalties payable by the Contractor. Typically, the Contractor will negotiate guarantees to reach numbers it is comfortable meeting, therefore minimizing the risk of having to pay the penalties. The levels of the guarantee and penalties agreed reflect Contractor confidence in the product/scope of supply, and also the competitive state of the market at the time of bidding.

The Converter station manufacturer has guaranteed the following [100]

- A maximum of 5 forced outages[101] per year on each individual pole averaged over a 3-year period
- The guaranteed pole forced energy outage[102] guarantee is 0.5%
- The forced bipolar outage rate guarantee is 0.1 or less outages per year
- There is no guaranteed bipolar forced energy unavailability
- The guaranteed scheduled[103] unavailability is 1.0%
- The scheduled energy unavailability is combined with the forced energy unavailability of pole and bipole outages for the purpose of application of penalties, *i.e.*, a total energy unavailability of 1.5%

The converter station guarantees do not include outages or events that are not within the Contractor's control. Therefore, they do not include outages caused by the HVdc OHL, electrode line, HVdc cables, ac lines or operator error.

Penalties associated with the guarantees incent the manufacturer to provide well designed and good quality equipment and systems, in order to minimize the risk of the penalties being applied. The evaluation procedure and penalties associated with the above guarantees are:

[100] PUB-NLH-248 to 258
[101] A forced outage is the consequence of protection action, and occurs with little or no warning.
[102] Cigre defines the forced energy outage guarantee as the energy that could not have been delivered if the system had been in full power operation, for the duration of the forced outage.
[103] A scheduled outage does not result from a protection trip, but is a shut down by the operator, and typically planned several days in advance. Planned outages; *e.g.*, to perform maintenance, have less significance than do forced outages, because the system operator will have been able to minimize the impact of the outage, by choosing the time of the outage and by putting into service other means for providing the power and energy resulting from the scheduled outage.

- The Pole and Bipolar forced outage guarantee is evaluated separately and its non-conformance penalty is applied separately.
- The forced outage energy guarantee is evaluated as the combined total of bipolar, monopolar and scheduled energy unavailability.
- The evaluation process for each guarantee is the same for all:
    - The conformance of each guarantee is initially evaluated over a 3-year period.
    - If the average performance (for pole outages calculated on an individual pole basis) does not meet the requirements, the Performance Guarantee Assessment Period is extended for an additional 12-months.
    - After this additional 12-month extension, the12 worst consecutive months are omitted from the calculation and the average is recalculated. If the average number of occurrences still does not meet the guarantee the Contractor must correct deficiencies and defects at no cost to the Company.
    - Once corrected, there is a further two-year evaluation period (which excludes the results of the previous four-year period and the period for correcting such deficiencies) to verify if the guaranteed reliability is met. If not, penalties are applied.
- Pole outages produce a penalty of $1,000,000 times the average number of outages in excess of the guarantee over the best 5 years (out of a total of 6 years).
- For the purpose of the forced energy outage guarantee, forced and scheduled outages have been combined, resulting in a combined guarantee of 98.5% energy availability. The penalty applied for non-conformance is $5,000,000 per additional average percentage above the guarantee during the best 5 years.
    - The combination of the forced and scheduled outages is, in our experience, unusual. Lower penalties are normally applied for the scheduled outages than for forced outages, since these can be planned to occur when most convenient to the owner of the HVdc scheme.
- The forced bipole outage non-conformance penalty is $5,000,000 times the average number of bipole outages per year during the performance assessment period.

The rate of the penalties seems relatively low, given the methods used for evaluation. The bipolar failure rate sets a particularly low hurdle, because two bipole failures in a 12-month period would be excluded for the second 4-year evaluation. Even if this hurdle is not met, one bipolar outage in the final two-year period would produce a penalty of just $200,000. However, market conditions do make negotiation of such conditions very difficult. Hydro's reply to PUB-NLH-475 states:

> *The performance guarantees were two of many terms and conditions in the contract for the supply and installation of the converter, and all terms and conditions in the supply contract were negotiated so as to achieve best overall value.*

4. HVdc Overhead Line(OHL)

The number of outages and the outage duration for failures associated with the HVdc OHL reflect directly on the overall reliability and availability performance of the LIL.

a. HVdc OHL Design Criteria

A technical assessment of the structural adequacy of the OHL is outside the scope of Liberty's engagement by the Board for this report. We have nevertheless reviewed all the information provided and discussed the matter with project personnel. Our interest is primarily on reliability and how the OHL integrity might affect bipole reliability and the impact of OHL-related bipole outages.

Hydro's position is that it has adequately designed towers and other components accordingly. We do not provide an opinion on the adequacy of the OHL design, however, we discuss the prospects for multiple tower failures, their impacts and associated restoration challenges in the appropriate sections of this report.

b. Bipolar Outages

The same towers will carry the overhead line conductors for the two poles. Therefore, a permanent bipole trip, resulting in a complete cessation of power delivery, will result from a tower collapse. Tower collapses may result from high winds and icing conditions. The likelihood of a tower collapse and its extent depends on the design criteria used for the towers.

A bipolar outage might also follow breakage of the Ground Wire (GW), if the falling GW makes contacts with both poles. High wind combined with high ice loading of the GW is an example of conditions that might produce this result.

NP-NLH-022 questioned the design criteria used by Hydro for the GW, making reference to clause 6.3.2 of CSA standard CAN/CSA-C22.3 No 60826.06. This clause states that some Canadian utilities have experienced as much radial ice weight on the GW as the larger diameter conductors. Hydro's design results in much lower weight than for the main conductor, because of the smaller diameter of the GW conductor. Accumulation of the same ice weight as for the main conductor would increase the risk of breakage of the GW, because the smaller diameter has lower strength.

In response, Hydro stated that it had no evidence to support spending additional funds to reinforce the ground wire and structures.[104]

c. Pole Outages

Pole outages can result from broken conductors or failed insulators. The cause of such faults is typically high winds and ice accumulation on the conductors and on towers. Vandalism can also cause insulator damage, resulting in reduced insulation capability and flashover, which may persist until a dc voltage reduction or insulator replacement.

[104] PUB-NLH-515

d. Temporary Faults

A temporary bipole fault could result from a flashover to ground caused by a severe lightning strike to an OHL tower with high earthing impedance, or by a forest fire in close proximity to the OHL line.

The HVdc control system responds to faults on the HVdc line by immediately stopping current flow on the affected HVdc pole. The control system then keeps the dc voltage at zero voltage for that period of time judged sufficiently long for the insulation strength of the air to recover. After this period of time, the dc voltage is ramped up to the normal value, and power transmission resumes. Power transmission typically returns to the pre-fault value in 300 to 500ms.

In cases of a forest fire, icing, or heavy pollution, a restrike may occur upon re-energizing the line. In such cases the HVdc control system reacts as explained above, but this time allows for a longer de-ionization. If this re-start attempt also fails, the HVdc control system may attempt to re-start at a reduced dc voltage (typically 80%). If this attempt succeeds, power transmission becomes possible at reduced capacity.

Hydro has not yet performed studies taking into account potential re-strikes after re-energization, but states that the converter station manufacturer will perform such studies.[105] The issue is that the inertia provided by the synchronous condensers may not be sufficient to keep the frequency above the UFLS trigger level in case of re-strikes,

e. Predicted Performance of the HVdc OHL

The response to PUB-NLH-212 attachment 2 summarized CIGRE documentation from 1998 to 2008 in respect of HVdc overhead lines as set out in the following table.

Table IV.1: HVdc Transmission Line Outage Statistics

System	Length km	Reporting Period(yrs.)	km-yrs.	No. of Outages	f/100km /yr./pole	Avg. Duration (hours)
Pacific	847	8	6,776	51	0.376	1.48
Nelson River-	960	11	10,560	45	0.213	0.53
Nelson River-	960	11	10,560	41	0.194	0.52
Square Butte	749	9	6,741	5	0.037	1.69
CU	710	11	7,810	6	0.038	4.72
Itaipu-1	1200	6	7,200	21	0.146	2.06
Itaipu-2	1200	3	3,600	10	0.139	0.24
IPP	784	3	2,352	18	0.383	2.96
Average					0.191	1.78

Based on the Cigre data, Hydro has suggested that, on average, the 1,100km long LIL HVdc OHL would suffer 2.1 outages per pole per year, requiring on average 1.8 hours to repair. The short repair time of 1.8 hours results because many of the failures in the sample do not require

[105] PUB-NLH-568

field repair, but merely an operator assisted restart of the line after a trip (perhaps because automatic restarting was not provided, or it failed). Other failures could have significant duration, requiring field repairs to restore the line to service.

Hydro has assumed a 2-week repair period for a major OHL failure[106]based on a summary of Hydro's response to ice storm damage since 1967. There were many outages longer than 14 days, but detailed restoration plans were identified as being necessary after the 63-day outage of the Buchans to Massey Drive failure, which involved seven failed structures. Since then, the longest outage is recorded as the 1994 failure which took 14 days to repair, and involved 6 conductor miles of the Western Avalon to Hardwoods circuit.

It must be recognized that repairing significant OHL damage in extreme weather and in the harsh terrain that some of the OHL line is situated will be challenging. Recognizing the magnitude of this challenge, it is hard to have confidence that two-weeks is the upper limit for repair for an OHL-related bi-pole outage.

Hydro has taken steps taken in the design of the HVdc OHL to minimize the probability of long term outages.[107] These steps include the provision of anti-cascade towers at intervals of every ten to 20 towers, and shortening of spans in areas with the most severe ice and wind loading.

The response to PUB-NLH-212 attachment 2 states that common mode failures, (*e.g.*, a tower collapse, which would result in a bipole outage) have been taken into account for the OHL. Using the Cigre information and the LIL line length has produced a suggested average annual bipole outage rate of 0.22 per year, with an average time for repair of 24 hours. Given that a tower collapse is most likely to occur during adverse weather conditions, the repair time of 24 hours seems short, but some bipole outages resulting from restrikes or pollution or smoke from ground fires might be "rectified" by manual re-energization, perhaps at reduced dc voltage (and capacity).

Hydro has taken advice from reputable consultants and institutions, and has had testing performed by STRI, Sweden to verify the insulator design for reliable operation, taking into account the salt and ice conditions expected along the route of the HVdc line.[108] While the assumptions made by Hydro may be reasonable; the actual outage time will vary significantly around the average number, because it will depend on the magnitude of equipment failure and the accessibility of the failure location.

f. Performance Guarantee

Hydro has responsibility for designing and building the HVdc OHL; therefore, no guarantee exists with respect to them. The performance assumed by Hydro in the calculation of reliability and availability of the LIL HVdc OHL can be summarized as follows:

- Number of bipole outages per year 0.22
- Average time to repair bipole outages 24 hours

[106] PUB-NLH-299 and GRK-NLH-033
[107] PUB-NLH-300
[108] PUB-NLH-240

- Number of pole outages per year 2.1 per pole
- Average time to repair pole outages 1.8 hours

5. HVdc Cable

Cable failures occur much less frequently than OHL failures, because the HV conductor is protected from the elements. However, when a cable failure occurs, the repair time may be very long, particularly on a sub-marine cable, and when weather conditions can be such that repairs cannot be performed during some parts of the year, as will be the case in the Strait of Belle Isle.

Hydro provided weather surveys for the cable crossing area,[109] showing that the number of September to April days with wave heights in excess of 2.5m (which would make cable retrieval and laying difficult) exceeded 5 per month. Naturally, high waves can also occur during the summer period, but not usually for a sustained period.

There is only limited public information available about HVdc cable failures. A Cigre survey offers one source of information (reported in Technical Brochure 379[110]). This document shows that 10,000km of dc cable similar to that used on LIL had been installed, with an average annual failure rate of 0.1 per 100 km per year. Half of these failures were due to external causes, with the reasons for the others unknown. The LIL uses 3 cables each 35 km long, so applying the survey result to LIL would result in one cable failure on average every 10 years.

The Cigre reliability performance surveys offer additional information, indicating that, for the years 2007 and 2008, dc cable failures on the Fennoskan, Kontek, Sacoi and Grita HVdc schemes occurred, with outage times ranging from 610 to 1624 hours. No information addresses the causes of any of these cable failures.

Steps to minimize the probability of cable failures have been taken in the specification of the HVdc cables and its protection, as will be described below.

a. Causes of Cable Failures

Some HVdc cable failures are listed as being unexplained, but are often believed to have resulted from mechanical damage to the cable sustained during the installation process. Sometimes such damage does not result in a breakdown for a substantial period (months or even years) after the energization of the cable. Purely internal electrical failures of HVdc cables; *i.e.*, without mechanical external forces having weakened the insulation, are said to be rare. Other causes of failures include mechanical impact (*e.g.*, where the cable has not been adequately protected from physical damage, either by trenching or rock berm placement) and the cable is hit by heavy anchors or icebergs or breaks because of continuous long term movements caused by tidal streams.

The risk that the HVdc cable would be struck by a rolling iceberg raised considerable concern for the LIL. Such an incident could render most manmade protection of the cable ineffective. C-

[109] DD-NLH-097
[110] Technical Brochure 379, Update of Service Experience of HV Underground and Submarine Cable Systems, Cigre 2009

Core addressed the potential for iceberg damage to the HVdc.[111,112] As a consequence of the investigation, which was based on observation in 2013 of icebergs in the Strait of Belle Isle, Hydro decided to increase the depth at which the HVdc cables would emerge to the seabed to 75m at Forteau and 70m at Shoal Cove.

C-Core recommended additional observations to confirm the iceberg rolling frequency, indicating that some uncertainty exists relative to the prediction of the frequency of potential iceberg strikes to the HVdc cables. Such observations occurred in 2015. Fifty icebergs were monitored, indicating an average rolling period of 6 days.

The review undertaken by Manitoba Hydro International in 2012[113] commented in section "4.4.3 Iceberg risks" on the scour data assessment in the area, which surprisingly had shown scouring at depths of 70 to 75m. It is believed that these marks may be from earlier glacial periods, but this conclusion cannot be positively confirmed. Therefore, a risk of iceberg damage may still exist even with the deeper exit points of the Horizontal Directional Drilling (HDD)[114] operation.

C-Core has undertaken additional analysis and modeling.[115] The C-Core report shows a significant reduction in risk of iceberg strikes of the cables, with a projected cable fault return period at a depth of 70m of 4,500 years (compared to the earlier period of 1,000 years).

b. Protection of the HVdc Cable

The probability of HVdc cable failures occurring because of external causes will be minimized by the following measures:

- Horizontal Directional Drilling (HDD) will be used from the shore to a depth of 70m at Shoal Cove and to 75 m at Forteau. The HDD operation has been completed and the casings installed, supporting the installation of the HVdc cables in the summer of 2016.[116]
- The cable will be routed from the exit of the HDD in deep water, and will be protected by rock berms on the seabed over a length of 26.5km.[117] The rock placement will be controlled from a Remotely Operated Vehicle, and video inspections will be subsequently performed on an as-required basis, with rocks being replaced as necessary.[118]

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[111] Iceberg Risk to Subsea Cables in Strait of Belle Isle, Muskrat Falls Project, Exhibit 35, http://www.pub.nl.ca/applications/MuskratFalls2011/files/exhibits/Exhibit35.pdf
[112] DD-NLH-051
[113] Report on Two Generation Expansion Alternatives for the Island Interconnected Electrical System, Volume 1: Summary of Reviews, January 2012
[114] This steerable trenchless method of installing underground pipe, conduit, or cable in a shallow arc along a prescribed bore path uses a surface-launched drilling rig, with minimal impact on the surrounding area.
[115] PUB-NLH-581
[116] DD-NLH-052
[117] DD-NLH-104
[118] DD-NLH-120

- Double armoring of the cables[119] increases the resistance to external damage to the cable and will provide additional protection during cable laying and rock berm placement.[120]
- A drag free zone has been established in the area of the HVdc cable, prohibiting scallop fishing, which is considered to be dangerous to the HVdc cable.[121]
- Distributed Temperature Sensing (DTS) will be employed on the HVdc cables.[122] This measure will ensure that in the event of overheating of the HVdc cables (*e.g.*, in the event of deposits of low thermal capacity around the cable), detection will occur prior to significant damage from overheating.

In response to an RFI concerning the risk of mechanical damage to the HVdc cable during rock berm placement, Hydro confirmed that the HVdc cable manufacturer has specified the maximum impact energy that the cable can withstand during this operation.[123] Hydro has also confirmed that the HVdc cable will be HV tested before and after the rock berm placement, in order to determine any damage caused by the rock placement as early as possible. However, as mentioned above, in some cases it has taken years for damage sustained during installation of the cable to result in a breakdown of the insulation.

The HVdc cable manufacturer has identified recommended spare components and storage requirements, to facilitate the repair of cable failures.[124] The cable supply contract includes the spare components. Hydro will therefore have 600m spare land and 8200m submarine cable, repair joints and other accessories to enable cable repairs to be performed, in the event of a failure.[125]

Repairs will require the cable to be lifted from the sea bed to a repair vessel where it is cut at some distance from the location of the breakdown in both directions from the fault. The cable would then undergo testing to ensure that the remaining sections are sound. After testing, a section of spare cable would be spliced to each of the sound ends of the original cable. The splicing operation requires specialists, to ensure that the repaired cable will provide reliable service for the rest of the life of the cable. The cable would then undergo testing again before being lowered to the sea bed, where it would be protected by rock berm, as required. The operation needs to be performed by experienced personnel, and requires the use of vessels equipped with special equipment to minimize the risks of the operation. Generally speaking, submarine cable repairs can only take place in relatively calm seas.

One potential problem with cable repairs arises from an intended minimum horizontal separation distance between the cables of as little as 50m. This relatively low distance results from the need to avoid shallow water, where iceberg strikes could happen.[126] The low distance complicates cable repairs, which involve retrieving the cable to a repair vessel for the insertion

[119] The cable is protected by two layers of steel wire.
[120] DD-NLH-105
[121] PUB-NLH-584
[122] DD-NLH-094
[123] PUB-NLH-473 and 474
[124] PUB-NLH-471
[125] PUB-NLH-239
[126] PUB-NLH-582

of a new section. The longer, repaired cable must then be "snaked" onto the seabed, to avoid crossing adjacent cables, making a minimum of two vessels likely needed.

c. Prediction of HVdc Cable Failure Rates

C-Core has investigated the possibility of potential damage of the HVdc cables by icebergs, against which rock berms are unlikely to be effective. C-Core has reported the possibility of simultaneous iceberg strikes on all 3 cables (resulting in the loss of all power transmission on LIL for a substantial period of time) as having a resulting failure rate of 0.001 (once in 1000 years), with an average annual outage time of 4.38 hours (*i.e.*, potentially a 6-month outage every 1000 years). The analysis, like all predictions of failure rates, used statistical methods, such as Monte Carlo techniques. Such analyses produce results only as good as the data provided as input to the calculation. The risk of an iceberg strike has recently been reduced to a return period of 4,500 years.[127]

Other causes of HVdc cable failures, (internal and external causes, such as fishing and shipping activities) are estimated in section 2.3 of the Reliability and Availability of the HVdc Island Link Report to result in a failure rate of 0.02 failures/year/cable, which produces an HVdc cable fault every 50 years for each cable.[128] This calculation differs from the failure rate of one cable failure every 10 years based on the technical brochure footnoted below.[129]

A single dc cable outage would not result in reduction of power transmission capability. Therefore, the probability of more than one cable being out of service has significant interest. If we assume, for example, a 6-month duration for a dc cable repair, and if we apply Hydro's assumptions of failure rates, the statistical probability of a further failure occurring on one of the remaining cables during the repair period becomes once every 800 years.[130] Hydro has calculated the probability as once every 453 years, with that calculation also taking into account the possibility of an iceberg striking two cables.

Obviously, any latent cable defect that results in pre-mature ageing of the cable or its components, would render these statistical calculations inapplicable. Hydro considers it highly improbable for more than one cable to remain out of service for the same period of time due to an iceberg related forced outage.[131]

d. Consequences of an HVdc Cable Failure

Failure of an HVdc cable can take it out of service for a long period of time. The minimum cable repair time, even with favorable weather conditions and full preparedness for the repair, likely involves several weeks, rather than days. An autumn fault may make it impossible to affect a repair until the next late spring. Therefore, the provision of three cables, which provides a spare in-service cable, given the two actually required, reflects a prudent configuration.

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[127] PUB-NLH-581

[128] Reliability & Availability of the HVdc Island Link, SNC-Lavalin, 10 Apr-2012, PUB-NLH-212,Attachment 2

[129] Technical Brochure 379, Update of Service Experience of HV Underground and Submarine Cable Systems, Cigre 2009 Iceberg Risk to Subsea Cables in Strait of Belle Isle, Muskrat Falls Project, Exhibit 35, http://www.pub.nl.ca/applications/MuskratFalls2011/files/exhibits/Exhibit35.pdf

[130] Reliability & Availability of the HVdc Island Link, SNC-Lavalin, 10 Apr-2012,PUB-NLH-212,Attachment 2

[131] GRK-NLH-034

A single cable failure will cause the faulted pole to be blocked and tripped. The faulted cable would then be disconnected using the dc switchgear at the dc switching station. The subsequent actions will depend on which cable has failed:[132]

- If one of the two cables operating in parallel has failed, then, after disconnection of the failed cable, the tripped pole can simply be re-energized to resume bipolar operation. This re-energization has to be achieved within 5 minutes, to avoid unacceptable overloading of the cable that remained in service. The scheme design allows this approach.
- If the cable operating on its own has failed, then the pole remaining in service will have two cables in parallel, and can continue with overload operation as is designed for a normal pole trip. To return to bipolar operation (which will reduce power losses and increase power delivery at Soldiers Pond), it would be necessary to transfer one of the dc cables to the other pole. This method would require a brief interruption of power flow on the pole in service in order to disconnect the dc cable to be transferred. To avoid UFLS, this operation is likely to be delayed until the loading in the IIS is low and the IIS generation is available to reduce the load on LIL. Following dc cable disconnection, the pole that was in service can restart, and the cable can then be connected to the other pole, which can then be re-started.

Hydro has confirmed that if the scheme is operated at high power in bipolar operation with just two cables (*e.g.*, after one cable has failed earlier) a second cable failure could result in load shedding in the IIS, because the cable has no long term overload capability.[133] Such a failure scenario may have a low probability, but it is not implausible, because of the long cable repair time that may be necessary if a dc cable fails in the autumn or early winter.

Hydro stated that it would prepare operating guidelines so that, in the event of a dc cable failure, the operator would restrict the power transmission on the LIL.[134] This guideline would avoid load shedding in the event of a further dc cable failure, but could result in restricting the LIL to the import of about 396 MW for the IIS use. Such restriction of power import could have implications for the planning of standby power generation resources for the IIS.

Operation of the LIL at higher power delivered to the IIS would require additional spinning reserve in the IIS, or power to be delivered immediately from Nova Scotia (for the Maritime Link to import power to the IIS) or additional interruptible load contracts in the IIS, to avoid load shedding as a result of a pole trip on the LIL. Hydro stated it will consider these options, as well as UFLS, when preparing the operating procedures.

e. HVdc Cable Guarantees

No guarantees apply to the HVdc cables. This is not unusual, as all of the cable vendors are very reluctant to enter into guarantees. The manufacturer's warranty covers the cables for 3 years

[132] PUB-NLH-235
[133] PUB-NLH-236
[134] PUB-NLH-236 and 237

following successful completion of the last of the three cable systems.[135] The warranty covers all defects and failures in design, material, engineering, workmanship and installation, and provides that all of the work and warranty work shall be fit for the purpose intended.

We understand that the HVdc cables may be installed in the summer of 2016, but that the LIL may not be fully operational until 2019. Should this timing occur, the HVdc cable warranty may have expired by the time the scheme is in operation.

5. Electrode Lines

The electrode line comprises an important part of the LIL, making it possible to instantly transfer from bipolar operation to monopolar operation. Outages of the electrode line could potentially immediately turn a pole outage into a bipole outage, producing the potential for major under-frequency load shedding. This risk arises because monopolar operation with injection of the return current in the station grounding mat (rather than into the sea electrode) would result in saturation of the converter transformer, which would lead to tripping because of high levels of harmonics.

a. Electrode Line Failure Modes

During normal bipolar operation, the electrode line will have very low current, and will operate at very low voltage. Therefore, while lightning strikes to the electrode can cause an insulation breakdown from the electrode line to the tower (which is grounded), this insulation breakdown is highly unlikely to be sustained, and the fault likely to clear without the need for tripping.

During monopolar operation, the electrode line will operate with the same current as the OHL conductors, but at much lower dc voltage. The electrode line will be fitted with arcing horns,[136] whose design will serve to extinguish any arc caused by a breakdown transfer to the arcing horns, after the arc has extended. Therefore, temporary blocking or tripping is not normally necessary in the event of lightning strikes or other events that do not create a permanent short circuit to ground on the electrode line.

Permanent electrode line faults to the tower or ground or open circuit conductors can result from tower collapse, failure of fittings, conductor failure, insulator damage or flying debris. Failures could happen to one or both electrode line conductors. A detection and protection system will identify open circuit and short circuit electrode line conductors, and support automatic steps to remove these faults.

With a fault to ground on either of the electrode line conductors, switches at both ends will open the affected line, with reinsertion following a period sufficient to allow restoration of the insulation, if the fault is temporary; *e.g.*, caused by a lightning strike. Similarly, for an open circuit, the affected electrode line will be disconnected, but in this case it will only be re-inserted by the operator after inspection and repair.

[135] DD-NLH-108
[136] Arcing horns are designed such that the length of any arc will extend, which will make it easier for the arc to extinguish.

b. Reliability of the Electrode Line

The response to PUB-NLH-212 attachment 2 estimates the reliability of the electrode lines. The electrode lines each have two separate parallel conductors, which reduce the probability of an open circuit line. However, with 2 conductors the probability of a short circuit to ground or an open circuit conductor increases.[137]

The two conductors operating in parallel have the capability to handle the 10-minute overload current and to operate continuously at 1.5 pu current. However, one conductor cannot operate continuously under such conditions.[138]

The impact of the limited current rating during one electrode line operation has not been taken into account in Hydro's analysis, but would result in a reduction in availability. This reduction arises from the necessity to reduce the duration for which monopolar operation can continue when operating at the 1.5 times overload conditions.

The electrode line from the Muskrat Falls converter station to the sea electrode is very long at 400 km. For most of this distance the electrode line is accommodated on the HVdc OHL towers. This aspect avoids the need to consider some common mode failures (*e.g.,* a tower collapse) separately for the majority of the distance (they are already accounted for in the HVdc OHL). However, it may be possible for a broken electrode line conductor to touch one of the pole conductors, thereby causing a permanent pole fault. This phenomenon will result in a pole to ground flashover and the potential need for repair to remove the contact between the pole conductor and the electrode line conductor.

During an outage of the electrode line, it is (in principle) possible to operate the LIL in bipolar operation by using the converter station ground mat as a return. The unbalance current between the poles can be controlled to a very small value (<10 A dc), assuming availability of the necessary transducers and control. However, a pole trip[139] during this operating mode would require tripping of the remaining pole, because heavy injection of current into the ground mat is not acceptable. Therefore, in order to reduce the risk of UFLS during this mode of operation, the import power would have to be restricted to a level that would not put the IIS at risk.

It would also be possible, if both poles of the HVdc OHL and cable are available, to operate the LIL in monopolar mode with metallic return, which is achieved by using the HV circuit of the other pole as the neutral return conductor. However, this operating mode would reduce the power delivered at Soldiers Pond considerably, because of the power loss in the metallic return conductor.[140]

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[137] Because there are double the number of components (clamps, insulators and crimps), the probability of a failure almost doubles.
[138] PUB-NLH-259 and 466
[139] Temporary blocking of a pole takes place in the event of a flashover to ground on one HVdc OHL conductor, and results in the return current flowing into the converter station ground connection during this operating mode.
[140] The imported power is estimated to be limited to about 490 MW (using the 1.5 times current overload capability).

c. Estimation of Electrode Line Outages

The response to PUB-NLH-212 attachment 2 uses CEA statistics to predict the reliability of the electrode line from Muskrat Falls. The data for wood pole distribution lines indicated that the electrode line could suffer 20 outages per year, with an average repair time of 8.2 hours.[141] However, line monitoring and normal operation at very low voltage, lead Hydro to suggest an outage rate 10 times lower. A number of factors make this reduction in outage rate reasonable:

- The monitoring and electrode line switching capability provided
- The low operating voltage compared with the voltage rating of the insulation
- The accommodation of the electrode line on the HVdc OHL for the majority of the distance in Labrador
- The use of arcing horns.

The assumption is also supported by the information provided in the response to PUB-NLH-548 and 549, Attachment 1.

An estimated outage rate of 2 per year, as suggested in PUB-NLH-212 attachment 2 seems very high. It is potentially unacceptable, given the potential for such outages to result in pole outages becoming bipole outages while the electrode line is unavailable, and for the power limitation that would occur in the event of the outage of one electrode line conductor. A single electrode line conductor cannot operate continuously at 150%. Therefore, during the outage of one conductor, the continuous current has to be limited to 1023 A,[142] which is equivalent to 358 MW being transmitted from Muskrat Falls during monopolar operation. Unless Hydro restricts power to this level, during this operating mode, some UFLS may become necessary in the event of the loss of a pole. Hydro has predicted that the return period of operation with one conductor out of service when the trip of a pole occurs during high load periods will be 1,600 years, thus producing only a very low risk.

d. Guarantee

Here, as for the HVdc OHL, there are no guarantees, because the electrode line will be designed and built by Hydro.

e. Conclusions

IV-1. The electrode line forms an important part of the overall HVdc circuit, and close attention is required for achieving high availability of this circuit.

IV-2. The electrode line design will cause flashovers, from the conductors to ground or to the tower, to transfer to the arcing horns such that the arc will self-extinguish as quickly as possible, which will reduce the number of outages caused by temporary faults, such as lightning strikes to the HVdc transmission line.

[141] This calculation is based on statistics of low voltage distribution lines.
[142] PUB-NLH-259

6. DC Switching Station

The dc switching stations at the junctions between the Strait of Belle Isle cables and the HVdc OHL enable the spare cable to be switched from one pole to the other. The stations use transducers to detect fault location (on the cable or the overhead line), and the protection will block the restart of the pole in the event of a dc cable fault.

The transducers will also help determine which cable has failed, and will de-energize the faulty cable. If the pole that continues in service has only one cable, then the healthy cable on the pole out of service will be discharged and subsequently re-energized as a parallel cable on the healthy pole. This operation will be achieved within 5 minutes, allowing removal of the cable overload condition.

a. Reliability Assessment

Hydro should have, but did not, take into account the dc switching station in the reliability and availability analysis of the LIL. A failure of insulation, equipment or the control and protection system could result in a pole outage or an inability to switch the spare cable from one polarity to the other, as may be required in the event of a permanent pole failure. The impact on the overall reliability and availability of the LIL will probably be relatively small, but will not be negligible.

Hydro's response to PUB-NLH-588 stated that the converter station manufacturer's report on Reliability, Availability and Maintainability (available at the end of 2016) will address the reliability and availability of the dc switching station.

7. Other Causes of Outages and Interruptions

Other causes of outages of the LIL or interruptions of power infeed to the IIS from Muskrat Falls, which have not been discussed in section two through seven above include:

1) Tripping of some or all ac lines leading to the Muskrat Falls converter station
2) Tripping of some or all ac lines leading to the Soldiers Pond converter station
3) Delayed clearing of faults in close proximity to the Muskrat Falls or Soldiers Pond converter stations, *e.g.*, because of protection or breaker failure (stuck breaker)
4) Major faults, *e.g.*, fire or extensive insulation damage to 2 or more high inertia synchronous condensers, requiring major repair at times of high loading on the LIL
5) Operator errors
6) Major fires in the converter stations.

The first three of these faults could result from circuit breaker failure[143] or from major weather problems (*e.g.*, ice, rime frost, snow, wind) that cause collapse of the network infrastructure.

[143] The protection system commands specific circuit breakers to open to clear faults. Normally, the breakers open in a couple of cycles, but sometimes the breakers fail to operate. If this happens, breaker failure operates commanding other circuit breakers to open, but these breakers will trip not only the detected fault, but also other segments of the ac network. For example, correct breaker operation could result in the tripping of one ac line, while the back-up protection could result in two or more ac lines and other system components being tripped.

These faults could result in a major reduction in the power that can be delivered to the IIS on the LIL.

The fourth fault could result in operational constraints to the power flow on the LIL, or operation could continue with accepted higher risk of UFLS.

Extensive training minimizes operator errors. The HVdc control system design seeks to stop incorrect actions through interlocking.[144] Nevertheless, human errors can occur.

Faults 1, 2, 3 and 5 often have relatively short duration, but could cause major UFLS. A fire in the control room, valve halls or plant rooms could result in an outage of the complete HVdc scheme, if it engages common equipment. If the fire is contained to the room in which it started, the impact may be limited to the loss of a single pole.

To prevent fire spread, equipment for the two poles are segregated in separate rooms, with rated fire walls where necessary and with fire protection systems for critical equipment rooms.[145] The use of combustible material will be minimized in the converter buildings, and fire protection systems will be provided for critical equipment rooms. Hydro will also take into account the recommendations made by its insurer in the design of the converter stations.

Major valve hall fires were experienced on some HVdc schemes several years ago, producing long outages (some more than 12 months). As a consequence of these fires, the use of combustible material in the valve halls has been minimized, and to our knowledge there have been no recent major valve hall fires.

None of the above risks are covered by guarantees, or have been considered in the information filed by Hydro. However, when assessing the overall performance and predicting the frequency and extent and duration of under frequency load shedding operations, the above listed causes for outages should also be considered.

8. Maritime Link Impact on Security of the IIS Power Supply

The guaranteed performance of the converter stations for the Maritime Link is similar to that of the LIL. PUB-NLH-261 provides the following data:

1. Mono-polar Forced Outage Rate:	*8 per year (4/pole/year);*
2. Bipolar Forced Outage Rate:	*0.1 per year (1 every 10 years);*
3. Mono-polar Forced Energy Unavailability:	*Unknown;*
4. Bipolar Forced Energy Unavailability:	*Unknown;*
5. Total Forced Energy Unavailability:	*<1%; and*
6. Scheduled Energy Unavailability:	*<1.5%.*

Overall, the annual energy availability has been guaranteed to be greater than 98%.

[144] Interlocking uses status signals from the equipment. Pre-set rules within the control system prevent damage or unwanted shut down of the HVdc scheme. For example, interlocking will prevent the energization of the converter if there is a closed grounding switch anywhere in the area to be energized.
[145] PUB-NLH-273

These guarantees are similar to those provided by the manufacturer of the LIL converters. The evaluation method and penalties are not known.

With the Maritime Link operating to export power from the IIS to Nova Scotia (the normal operating mode) a trip of the Maritime Link will not present a major risk to the IIS power supply security, as long as the LIL is in operation. The LIL includes frequency control of the ac network, so that in the event of a trip of the Maritime Link, the LIL will quickly reduce the import from Muskrat Falls generation to prevent over-frequency of the IIS.[146]

Furthermore, in the event of a power supply problem from Muskrat Falls to the IIS, *e.g.*, due to a pole or bipole trip, the Maritime Link can be curtailed, as described earlier as if it were an interruptible load. The curtailment of the Maritime Link will effectively reduce the power supply shortfall from the LIL by the amount of power being exported, thereby minimizing the loss of power infeed to the IIS.[147]

If the Maritime Link were to export power to Nova Scotia when the LIL is not in service (an unlikely operating condition) there could be a risk of unacceptable frequency excursions as a result of the trip of both or the only pole of the Maritime Link (increased frequency) or as a result of a trip of island generation (falling frequency). System Control can manage these issues operationally by restricting power flow on the Maritime Link in accordance with good utility practice. The Maritime Link has the possibility to provide frequency control of IIS; this control mode would also alleviate the potential problems.

If the Maritime Link were to operate to import power to the IIS from Nova Scotia, *e.g.*, in the event of a supply problem from Muskrat Falls or other reasons, a supply security issue could arise. When the Maritime Link operates as a bipole, such issues could be alleviated by ensuring that the Maritime Link operates with a frequency controller that would ensure maintenance of the IIS ac frequency in the required range. This method would permit survival of load and generation trips in the IIS system. Obviously, a complete trip of the Maritime Link could affect the IIS, leaving System Control to manage the resulting impacts.

The preceding discussion has focused on the real power issues associated with the Maritime Link. However, the Maritime Link will also provide a valuable reactive power control service. A trip of the Maritime Link could therefore also have an impact on the ac voltage control in the IIS.

The response to PUB-NLH-565 provided a new study report titled “Maritime Link VSC HVdc Run-Back Requirements – PSS/E Dynamic Contingency Analysis”. This report looks at 11 different base cases, and 6 different fault cases. The study identified benefits associated with the installation of a new 50Mvar shunt capacitor bank near the Bottom Brook converter station.

[146] PUB-NLH-262, and 447
[147] PUB-NLH-263

a. Conclusions

IV-3. When the Maritime Link is exporting power from the IIS to Nova Scotia, the ability to curtail the Maritime Link provides significant benefits to the IIS.

IV-4. It would be beneficial to the IIS if the Maritime Link were operated with back-up[148] frequency control for the IIS system, both when the LIL is in-service and not in service.

The ancillary service[149] of frequency control would enable the Maritime Link to provide further benefits to the IIS when operating in either import or export mode. A commercial arrangement would have to be negotiated with Emera to provide for this.

Recent power system studies performed by ABB have found benefits in activating the frequency controller in the Maritime Link VSC control system.[150] The benefits accrue to Nova Scotia in the event of generator trips in Nova Scotia and to the IIS, e.g., in the event of faults close to Bay d'Espoir, and permanent and temporary LIL pole and bipole faults. The LIL converter station manufacturer is performing further detailed studies. If the work identifies benefits to the overall frequency response in the IIS and corresponding UFLS operations, terms and conditions for this service would have to be negotiated.

B. Dynamic Performance of the HVdc Scheme

In addition to trying to estimate the number of pole and bipole outages that may occur due to equipment and other failures on the LIL, it is important to establish the impact that temporary faults and permanent trips of the LIL and of equipment in the ac networks, e.g., synchronous condensers, will have on the performance of the ac network. The issue here is whether or not the ac voltage and ac frequency can be kept within the required limits, to avoid the need for under-frequency load shedding.

Several studies by Hydro and its consultants have examined the impact on the IIS from faults within the LIL or in the ac networks close to the converter stations.[151,152,153] The earliest studies analyzed a 3-terminal HVdc scheme from Gull Island to Soldiers Pond and Salisbury, New Brunswick. Later studies concentrated on connections from Muskrat Falls to Soldiers Pond, and included the interactions between the LIL and the Maritime Link. All of the later studies also included two new proposed 230kV lines, one connecting the Maritime Link from Granite Canal

[148] A back-up frequency control would become active only when the frequency of the IIS was outside a defined range. This method of control would prevent unnecessary interactions between the frequency controllers in the IIS, the LIL and the ML.
[149] An ancillary service is provided to benefit the operation of an ac network. It can be provision of reactive power, frequency control, back-up power, etc.
[150] PUB-NLH-570 and 572
[151] Lower Churchill Project, dc1210 – HVdc Sensitivity Studies, Final Summary Report, July 2010.
[152] Lower Churchill project, Stability studies, SNC-Lavalin, 06-Mar-2012, SLI Document No.: 505573-480A-47ER-0004-01.
[153] Maritime Link Preliminary Interconnection Study, Newfoundland and Labrador Hydro, July 2014, PUB-NLH-264, Attachment 1.

to Bottom Brook, and one additional line from Bay d'Espoir to Western Avalon. The later studies are discussed in the following sections.

The main criteria used for all studies when assessing the acceptability of the results are stated in the Hydro Transmission Planning Manual and are summarized below.

- The system should be able to sustain the single contingency loss of any transmission element without loss of system stability
- The system should be able to sustain a successful single pole reclose[154] for a line to ground fault
- Multi-phase 230 kV faults shall be cleared in a maximum clearing time of 6-cycles
- Load shedding should not occur for the loss of the largest generator in the IIS
- Load shedding should not occur for the temporary loss of a pole or bipole of an HVdc link
- The system response should be stable and well damped
- Post-fault recovery voltages on the ac system shall be as follows:
    - Transient under-voltages following fault clearing should not drop below 0.7 pu
    - The duration of voltage below 0.8 pu following fault clearance should not exceed 20-cycles
    - Post-fault frequencies should not drop below 59 Hz
    - Under-frequency load shedding should be minimized.

The assumptions underpinning the study results were as follows:

- Following a temporary bipole fault the bipole can recover to full power within 300ms, including a 175ms de-ionization[155] period before re-energization of the HVdc line.
    - However, as the ac voltage at Soldiers Pond was found in some studies to be depressed to 0.8pu or lower,[156] because of the fast restart of the HVdc converter, an alternative slower and staged re-start was also modeled and resulted in the ac voltage being kept at more than 0.9 pu during the recovery period. The slower restart means that additional energy is lost from the system, i.e., in a deeper frequency drop.
- All ac system faults would be detected and cleared within 100ms.
    - Hydro uses two separate protection systems to detect faults and to open the necessary circuit breakers within 6 cycles.
    - However, in the event of a breaker failure[157] a much longer fault clearance time will result, and the tripping will involve further equipment.

[154] When the protection detects a fault to ground on only one of the phases it will open only the breakers associated with that phase, and will then reclose these breakers after a time period sufficiently long for typical temporary faults to have self-cleared.

[155] Temporary faults are normally caused by a flashover to ground. The flashover causes an arc between the line and ground, the arc consisting of very high temperature gas. When the power is removed by converter action, the arcing to ground stops, and the high temperature gas gradually dissipates.

[156] The ac voltage is lower than normal (depressed) because the converter absorbs more reactive power than normal during the recovery period, and the reactive power resources (ac harmonic filters and synchronous condensers) are unable to provide sufficient reactive power to restore the ac voltage amplitude to the normal level.

[157] A breaker fault can be caused by the protection trip signals not reaching the breaker mechanism, or can be caused by an actual fault in the breaker. The latter is sometimes referred to as a stuck breaker.

  - Hydro has identified a breaker failure at Muskrat Falls as a worst case scenario, which will result in a bipole outage and under-frequency load shedding in the IIS.[158] This scenario is considered to be an N-2 event, and therefore Hydro considers it acceptable to result in UFLS.
- For some study cases, the ML power export was reduced to 0 MW approximately 200ms after fault inception. This action was found to be necessary to avoid system instability in case of the following faults:
  - Three phase ac line faults at Muskrat Falls
  - Three phase ac system faults in Western Avalon
  - Temporary Bipole faults
  - Permanent Pole faults
  - Loss of largest generator within the IIS
  - Loss of synchronous condenser at Soldiers Pond.
- In the event of a Pole trip the current on the remaining pole is quickly increased to 2.0 pu direct current.
  - During the period after the recovery, the synchronous condensers were providing reactive power support in excess of their rating. This result was considered acceptable, because tap change operations on the remaining pole would gradually reduce the converter firing angle and therefore reduce the reactive power absorbed by the converter. Each step of the tap changer typically takes 7 seconds and changes the voltage by about 1.5%.

1. Lower Churchill Project – Stability Studies

SNC-Lavalin performed this 2012 study, which Hydro attached to its application for the improvement of the transmission corridor between Bay d'Espoir and Western Avalon. (SLI Document No.: 505573-480A-47ER-0004-01).[159] This study's configuration is very similar to the one currently being implemented. The Maritime Link was represented as an LCC HVdc scheme, because the technology to be used for the Maritime Link was not known at the time. Both HVdc schemes included frequency controllers.[160] An SVC was modeled at Bottom Brook, to ensure that sufficient reactive power would be available for the needs of the ac network.

The study investigated the performance of the LIL and the impact on the IIS. The study assumed new 230kV lines from Bay d'Espoir to Western Avalon, and from Granite Canal to Bottom Brook to be in service. The study determined the approximate HVdc control algorithms required and the need for synchronous condensers in the IIS.

The study was performed based on the export on the Maritime Link being reduced to zero over a 200ms period in any event resulting in significant reduction in system frequency.

[158] PUB-NLH-241 and 472
[159] Lower Churchill project, Stability studies, SNC-Lavalin, 06-Mar-2012, SLI Document No.: 505573-480A-47ER-0004-01
[160] Frequency controllers are used to change the power flow on the HVdc scheme, to help the frequency of the system to return to the normal value, *e.g.*, in the event of the sudden loss of generation or load.

The study addressed the following fault cases:

- Temporary Bipole Fault on the LIL
- Permanent Pole Fault on the LIL with post-fault monopolar operation
- 3-phase/6-cycle fault at Muskrat Falls 315 kV on 315 kV line to Churchill Falls
- 3-phase/6-cycle fault at Bay d'Espoir 230 kV on 230 kV line to Western Avalon
- 3-phase/6-cycle fault at Soldiers Pond 230 kV on 230 kV line to Western Avalon
- 3-phase/6-cycle fault at Bottom Brook 230 kV on 230 kV line to Granite Canal
- 3-phase/6-cycle fault at Stony Brook 230 kV on 230 kV line to Bay d'Espoir
- 3-phase/6-cycle fault at Bay d'Espoir 230 kV on 230 kV line to Sunnyside
- 3-phase/6-cycle fault at Bay d'Espoir 230 kV with post-fault outage of Bay d'Espoir G7

The study did not examine the trip of the last remaining pole when operating in monopolar operation, because this condition is considered an N-1-1[161] contingency. Similar to a bipole trip, this condition is considered to be permitted to result in load shedding, if necessary. The studies were performed based on a PSSE model, which had been used for earlier studies on similar, but not identical, configurations of the HVdc scheme. The studies showed that the worst case occurred for peak winter loads with the LIL operating at maximum power.

The study found that a three phase ac system fault at Bay d'Espoir on the Western Avalon line would result in a rapid decrease in frequency and low ac voltage, with high overloads on the reactive power output of the synchronous condensers, and in some cases a bipolar trip of LIL. Similar results occurred for the cases involving faults at Bay d'Espoir on the line to Sunnyside during a generator outage.[162]

In order to achieve satisfactory performance, it would be necessary to have either:

- 450Mvar high inertia synchronous condensers at Soldiers Pond and an ±250Mvar SVC at Bay d'Espoir
- a third synchronous condenser at Holyrood and increase the total synchronous condenser rating at Soldiers Pond to 450Mvar.

In the existing isolated island system, faults at Bay d'Espoir are accepted as an "Exceptional Contingency," with UFLS activated to prevent system collapse.

Hydro stated that it will minimize the probability of this event causing UFLS by planning the maintenance of the synchronous condensers so that all three high inertia synchronous condensers at Soldiers Pond will be operational for the winter season.[163] Furthermore, all three

[161] An N-1 condition is defined by Hydro as an operating condition where a major transmission asset (e.g., 230kV or 138kV transmission lines, shunt capacitor banks, synchronous condensers or a transformer) has been lost, either due to maintenance or a fault. For an N-1 condition no loss of supply to consumers should occur. Note that outages of single radial lines and other single events, which are considered to be very low probability may be allowed to result in the loss of some consumers.
An N-1-1 condition is a further loss of a major transmission asset, when the system is already in a N-1 condition. See PUB-NLH-186 for further information.
[162] PUB-NLH-484
[163] PUB-NLH-484

high inertia synchronous condensers at Soldiers Pond will be planned to be in service during high LIL deliveries to the Island.

The SNC-Lavalin report addressed an examination carried out to determine the implication of extending the temporary bipole restart time, as may be necessary because of the need to keep the ac voltage at Soldiers Pond above 0.9 pu (to minimize the risk of commutation failure),[164] or because of potential restrikes of a fault on the HVdc OHL. A slower power recovery results in a greater fall of the ac system frequency, and therefore a risk of UFLS. The permitted maximum re-start times with different numbers of synchronous condensers and the LIL operating at maximum power that resulted were:

- 2x150 Mvar synchronous condensers on-line, maximum re-start time = 12-cycles/200 ms
- 3x150 Mvar synchronous condensers on-line, maximum re-start time = 23-cycles/380 ms
- 4x150 Mvar synchronous condensers on-line, maximum re-start time = 34-cycles/567 ms.

Hydro proposed to install three 150 Mvar high inertia synchronous condensers, later increased to 175Mvar.[165] Hydro expects to operate with all three high inertia synchronous condensers in service during high load periods during the winter peak period. To save power losses, Hydro plans to operate during most of the other parts of the year with just two high inertia synchronous condensers in service.

In the event of a restrike (*i.e.*, the fault on the HVdc OHL reappears as soon as the dc voltage increases towards the rated value) the total outage period would at least double (because of the need for two fault clearances). The outage period would thus become 600ms or more, and UFLS may be triggered. The frequency of the occurrence of restrikes can be reduced by increasing the time allowed for de-ionization.

The risk associated with having only 3 high inertia synchronous condensers is recognized in the report. In particular, a fault in one of the synchronous condensers could make this unit unavailable for service for many months, and during this time there would be a risk of major UFLS, in the event of an ac fault near Bay d'Espoir.

The SNC-Lavalin study also identified potential requirements for reactive power control at Bottom Brook. However, since that 2012 study, the converter technology selected for the ML was VSC HVdc. This selection means that the converter station at Bottom Brook, when in service, can provide reactive power support for the local ac network. Hydro will evaluate the

[164] Commutation is the term used for the transfer of current in the converter from one phase to the next. In a modern 12 pulse converter, this event takes place 12 times per cycle. The commutation depends on the ac voltage being reasonably sinusoidal. If the ac voltage is distorted, e.g., because of a remote ac fault, commutation can be unsuccessful and a dc temporary fault occurs, which is automatically cleared by the control system, but the result is a brief (<50ms) interruption in power flow.
[165] PUB-NLH-271 and 440

need for additional reactive power compensation in planning studies scheduled to run through 2016.[166]

Meanwhile, the response to PUB-NLH-562 provided extracts from a study showing that, in the event of the loss of power transmission capability on one pole of the Maritime Link (stopping dc power flow), the converter switches to reactive power control mode and satisfactorily controls the ac network voltage.

One major result of the study was the determination that curtailment of the Maritime Link, in response to major system events, would provide a powerful solution to the avoidance of UFLS.

2. Maritime Link Preliminary Interconnection Study

A more recent preliminary dynamic system analysis, the August 13, 2014 "ML, Preliminary Interconnection Study," was filed with PUB-NLH-264 as Attachment 1.[167] This study investigated the performance of the IIS during and after a number of faults, taking into account both the LIL and the ML. The faults investigated were:

- Faults at Bay d'Espoir
- AC Transmission Line Faults in Western Newfoundland
- Temporary Bipole Faults
- Permanent Pole Faults
- Loss of Generation within the Island System
- Loss of a Synchronous Condenser at Soldiers Pond

The study excluded bipole trips, because of the knowledge that such faults will result in extensive UFLS. While it is accepted that bipolar faults will result in UFLS, bipolar outages should be studied as part of the Interconnection Study and the Operational Studies. Such analysis has the benefit of providing assurance that the bipolar outage will not result in a total collapse of the IIS.

The starting point for the studies was similar to the 2012 SNC-Lavalin study discussed above, but differed by using three high inertia synchronous condensers with a rating of 175MVA (one assumed to be out of service), and the inclusion of a new 60 MW gas turbine at Holyrood (HRD) operating as a synchronous condenser. Furthermore, the reactive power capability of ML (125Mvar per pole) was taken into account.

Studies were carried out for a number of different system conditions:

1. *System loading conditions (i.e., heavy, intermediate, light, and extreme light)*
2. *Island dispatch (i.e., maximum generation, economic dispatch, or minimum generation)*
3. *Import to the Island Transmission System over the LIL (i.e., 0 MW to 830 MW)*
4. *Export over the Maritime Link (i.e., 0 MW to 500 MW).*

166 PUB-NLH-488
167 Maritime Link Preliminary Interconnection Study, Newfoundland and Labrador Hydro, July 2014

The report summarizes the results of the studies and the immediate actions required by the Maritime Link, as shown in the next table.

Table IV.2: Summary of Transient Stability Analysis

Contingency	Required Remedial Action
Faults at Bay d'Espoir	No Action Accepted as "Exceptional Contingency"
Faults at Bottom Brook, Buchans, Granite Canal, Massey Drive, Stony Brook, and Upper Salmon	Curtailment of ML Export to 250 MW.
LIL Temporary Bipole Faults	Curtailment of ML Export to 250 MW.
LIL Permanent Pole Faults	Curtailment of ML Export to 250 MW or 0 MW.
LIL Faults While in Monopole Mode	Curtailment of ML Export to 0 MW.
Loss of Island Generation	Curtailment of ML Export to 250 MW or 0 MW.
Loss of a Synchronous Condenser at Soldiers Pond	Development of Operating Instruction to avoid unacceptable system conditions.

The study showed that a fault at Bay d'Espoir would produce system instability under heavy load conditions. The instability results in UFLS. Hydro does not propose any mitigation to avoid UFLS, and has accepted this fault as an "Exceptional Contingency". The study also showed that, during most other fault conditions, curtailment of export on the Maritime Link becomes necessary to meet system planning criteria.

The study also showed that when in monopolar operation at high load, a permanent pole failure will result in UFLS. Hydro considers monopolar operation an N-1 condition, which makes UFLS acceptable to Hydro when that pole trips. Hydro states that "*In order to minimize operation risk, it is not Hydro's intent to operate at high LIL loading in monopolar mode for extended periods of time unless an emergency exists*".[168]

Hydro plans to perform maintenance of the poles (one at a time), during light load periods. Typically, operators rectify converter station faults as soon as possible, to minimize the duration of monopolar operation. However, for major events, such as the failure of a converter transformer, the outage could last up to a week, and much longer in cases of converter station fires.

[168] PUB-NLH-477

The HVdc converter manufacturer will perform additional studies as part of its contract, which may confirm the proposed actions in the above table, or recommend additional actions. These studies were not available at the time of this report.

3. Maritime Link Run Back Study

In May 2016, Hydro provided a copy of the report titled "Maritime Link VSC HVdc Run-Back Requirements, PSS/E Dynamic Contingency Analysis".[169] This report summarizes Hydro PSS/E studies. It appears that these studies did not use the PSS/E models developed by the manufacturers of the LIL and the Maritime Link, but instead the most up-to-date general and applicable models available to the public. The main purpose of the studies was to determine any additional reinforcements and control schemes appropriate for ensuring that the IIS remains stable following disturbances. The studies used assumptions similar to those described in Section 2 above. The transient analysis criteria are identical to those for the previously performed studies. The study emphasized post-fault voltage requirements, in particular the 70% minimum voltage limit and the 20 cycle time limit on voltages below 80%.

Base cases are identical to those presented in other studies, adding a condition placing the LIL out of service and assuming Maritime Link imports of 310 MW to the IIS.

Table IV.3: Base Case Scenarios Studied

Case	System Condition	Island Load (MW)	LIL Operating Mode	LIL Power @ MFA (MW)	Island Generation (MW)	ML Operating Mode	ML Power @ BBK (MW)
8001	Peak Load	1757	Bipole	900	1085	Bipole	158
8002	Peak Load	1588	Bipole	677	915	Bipole	158
8003	Peak Load	1594	Bipole	900	1075	Bipole	350
8004[170]	Peak Load	1471	OFF	0	1258	Reverse Power	-310
8005	Intermediate Load	1261	Bipole	676	1085	Bipole	158
8006	Intermediate Load	1261	Bipole	900	1085	Bipole	500
8007	Extreme Light Load	400	Bipole	415	335	Bipole	337

The report provided did not include any results for case 8004. The studies of faults at Bay d'Espoir with the new model of the Maritime Link improves performance to the extent that angular instability and UFLS does not occur, provided that the LIL is operated with reserve and with the Maritime Link curtailed or run back.

The provision of a new 50 Mvar shunt capacitor at Bottom Brook alleviates the low ac voltage problem, thus solving the reactive power problem discussed earlier. In some cases, the provision

[169] PUB-NLH-565
[170] Hydro document: Base Case 8004 simulates an extreme case where the LIL has been forced out of service due to a permanent bipole fault during the winter peak heating load season. In this case NLH will import up to 310 MW of power at Bottom Brook from NS to supply the maximum amount of customer load. (Note that the feasibility of such imports has not yet been determined). This case is considered by Hydro to be an N-2 contingency event prior to applying additional disturbances to the system.

of the shunt capacitor makes run-back of the Maritime Link unnecessary. Similarly, ac transmission line 3 phase faults in Western Avalon would also result in system instability and unacceptably low recovery voltages, without the Maritime Link curtailment and/or provision of a 50 Mvar shunt capacitor bank at Bottom Brook. The study of temporary bipole faults found curtailment of the export on the Maritime Link unnecessary to meet the planning criteria. Table 17 from the response to PUB-NLH-565 provides a summary of the study results for permanent pole and bipole faults, including the worst case amount of load shedding.

Table IV.4: Notable System Conditions Following Permanent Pole/Bipole Faults

Base Case	Contingency	System Condition		ML Curtailment (MW)	Load Shed (MW)
8001	LIL Permanent Pole Fault	Stable System	UFLS	0	87
			No UFLS	158	0
	LIL Permanent Bipole Fault	UFLS is Activated, *System Collapse*		158	519
8002	LIL Permanent Pole Fault	Stable System	No UFLS	0	0
			No UFLS	158	0
	LIL Permanent Bipole Fault	UFLS is Activated, *System Collapse*		158	516
8003	LIL Permanent Pole Fault	Stable System	UFLS	0	132
			No UFLS	350	0
	LIL Permanent Bipole Fault	UFLS is Activated, *System Collapse*		350	336
8005	LIL Permanent Pole Fault	Stable System	No UFLS	0	0
			No UFLS	158	0
	LIL Permanent Bipole Fault	UFLS is Activated, *System Collapse*		158	395
8006	LIL Permanent Pole Fault	Stable System	UFLS	0	66
			No UFLS	500	0
	LIL Permanent Bipole Fault	UFLS is Activated, System Stable		500	240
8007	LIL Permanent Pole Fault	UFLS is Activated, *System Collapse*	No UFLS	0	0
			No UFLS	337	0
	LIL Permanent Bipole Fault	UFLS is Activated, *System Collapse*		0	103
		UFLS is Activated, *System Collapse*		337	0

The study of permanent pole trips showed curtailment of the Maritime Link is necessary in most cases to avoid UFLS. High speed communication provided between the LIL and the Maritime Link will facilitate curtailment of the Maritime Link in the event of permanent pole or bipole faults.

The only base condition that avoids system collapse in the event of a permanent bipole fault is 8006 shown in the preceding table. The studies used the present UFLS scheme. The report includes the following statement: "Adjustments made to the UFLS protection system may be able to prevent other bipole trips from collapsing the Island Interconnected Transmission System, which is outside the scope of this study."

The study of generator trips showed that, with curtailment of the Maritime Link, only base case 8002, with a 3-phase fault and trip of Bay d'Espoir Generator 7, could not recover. Some other generator trips also required curtailment of the Maritime Link to prevent UFLS.

Table 20 of the report provides the worst case contingencies results. The table identifies the cases and conditions for static reactive power support and/or minimum curtailment from the Maritime Link. The table shows that the installment of shunt capacitors at Bottom Brook will have an impact on the level of required curtailment of the Maritime Link.

The study also identified possible thermal overloads on some transmission lines during operation of the Maritime Link at loads higher than 250 MW, should there occur a trip of one of the 230kV lines to Bottom Brook. This problem can be resolved by run back of the Maritime Link. The report indicates that the more advanced models of the LIL and Maritime Link, when assuming use of the curtailment/run-back of the Maritime Link, produce significant improvement in system performance when compared with the results of the earlier studies.

Hydro needs to perform significant additional work to ensure that the probability of a total collapse of the IIS is minimized to an acceptable, affordable level. Redesign of the present UFLS scheme is required, as the dynamics of the IIS with the large ratings of the LIL will drastically differ from those of the present IIS ac network.

The converter station manufacturer will perform studies, including temporary and permanent bipole faults, with tuned controllers; these studies will provide the best prediction of the actual performance of the LIL, the Maritime Link and the IIS.

4. Redesign of UFLS Scheme

The response to PUB-NLH-265 identified that the studies performed by SNC-Lavalin in March 2012 identified load-shedding needs for cases other than bipole trips. Hydro explained that such load shedding resulted from use of the existing UFLS scheme. That scheme included a df/dt[171]

[171] df/dt is the rate of change in frequency versus time. The frequency is monitored and the rate of its change is used as an input to the UFLS scheme. Normally, the faster the frequency changes, the quicker the need to respond and the more load needed to be disconnected to ensure that the situation does not become untenable. However, with an HVdc scheme, which is able to change power much more rapidly than a generator, the existing setting is not appropriate.

setting that had been triggered, even though load shedding would not have been necessary for the particular events in question.

Similarly, the Maritime Link Run Back study referred to above included cases where unacceptable system performance occurred, despite the occurrence of UFLS. Hydro again explained this result as due to the use of the present UFLS scheme in the study.

The dynamics of the IIS will change with the addition of the LIL and the Maritime Link, making it necessary to perform extensive system studies to ensure that the UFLS scheme will not respond unless required, but will respond to protect the network when necessary to prevent a total system collapse. Hydro states that it plans to change the UFLS scheme when the LIL enters service, to avoid unnecessary load shedding.[172]

Hydro's response to PUB-NLH-536 addresses the advantages and disadvantages of df/dt settings for the UFLS, for the large range of different system conditions that may exist in the future. The response suggests that the studies to be performed may conclude that df/dt protection may be restricted to very high rates of change, as may happen in the event of a bipole trip or the simultaneous loss of several generators in the IIS.

Hydro's response to PUB-NLH-535, which asked for a progress report on the determination of the post LIL UFLS settings, stated that post LIL, UFLS will only occur for double contingency faults. Hydro confirmed in its response to PUB-NLH-533 that post-LIL, the frequency of UFLS events will be significantly less than the current levels.

The UFLS scheme is vital to the avoidance of IIS collapse. The total collapse of the system from a bipole trip is obviously a catastrophic and unacceptable event, but the present scheme is not capable of avoiding it, as has been shown in section V.B.3. Detailed system studies need to be performed by Hydro for a wide range of IIS and LIL operating conditions, and these studies are planned for the second part of 2016. We have no reason to doubt Hydro's ability to devise the required new UFLS scheme, but the critical importance of this dictates that it be a high priority for Hydro as well as the Board in its oversight role.

5. Shut Down Time for ac Faults

AC faults are assumed to result in a shutdown time of 200ms, which includes 100ms for fault clearance and 100ms for power transmission on the LIL to recover to the pre-fault value. The period of 200ms seems very short; in our experience network operators usually make allowance for faults being cleared by back-up protection. Hydro justifies the time by the use of two separate and independent protections, which will detect the fault and trip the breaker.[173]

Hydro accepts that in the case of a breaker failure[174] the fault will have to be cleared by back-up protection, and states that the fault clearing time in the event of a breaker failure will be 12-19

[172] PUB-NLH-483
[173] PUB-NLH-241
[174] A breaker failure may happen either because of a mechanical issue with the breaker itself, or because of a problem with the protection system that should trip the breaker. Breaker failures may also be referred to as a stuck breaker.

cycles (200-300ms), resulting in a total shutdown time of 300 to 400ms. Furthermore, back up protection will typically result in the tripping of more equipment, because the back-up breaker(s) covers a greater area (more equipment is tripped).

Hydro posits a worst case fault as a stuck/failed breaker at Muskrat Falls bus 823 or 833, which will result in a trip of both an HVdc pole and a 315kV transmission line. Shortly after the trip of the pole and the ac transmission line, the remaining pole at Muskrat Falls experiences multiple commutation failures[175] and the other pole trips. A bipole outage resulting in the need for UFLS in the IIS becomes the overall result.

Hydro's response to PUB-NLH-555 stated that a reconfiguration of the terminal station would not solve the problem, concluding that:

> *For the system to be able to withstand a sustained three-phase fault in the range of 300 ms (*at MF*) as discussed in Hydro's response to PUB-NLH-241, significant inertia and reactive support would be required at both Muskrat Falls and Soldiers Pond to assist with voltage and frequency recovery. Preliminary analysis indicates that stability cannot be maintained, even with three high-inertia synchronous condensers[176] installed at Muskrat Falls Terminal Station and three additional synchronous condensers installed at Soldiers Pond Terminal Station. Such a solution would therefore not be practical.*

Hydro points out that, according to the NERC criteria, the simulated fault would comprise either a:

- Category C contingency (if a single line to ground fault), for which the ac network must remain stable and within limits and the loss of load or curtailed demand should be planned and controlled, or
- Category D contingency (if a 3-phase line to ground fault), which could potentially involve substantial loss of customer load and generation over a widespread area.

Therefore, Hydro considers the planned UFLS, which would occur for the rare event of a stuck/failed ac breaker, an appropriate, acceptable response.

Hydro identified 30 breaker failures in the period from 1996 to 2015, 7 of which resulted in customer outages, with a duration of up to 383 minutes.

Hydro has developed a detailed protection and control systems action plan to address issues associated with breaker failure protection system design.[177] Hydro reported in the response to PUB-NLH-554 the following progress:

- A review of 230kV substations has been concluded and updated protection has been installed in 6 of the 8 sites requiring corrective action.

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[175] Commutation failures at the sending end of an HVdc scheme are relatively unusual, but can be caused by a very distorted ac voltage.
[176] For simulation purposes, synchronous condensers were assumed to be equivalent to Soldiers Pond units.
[177] CA-NLH-034

- At 66kV and 138kV stations, 20 stations were identified as requiring action, and action has been prioritized according to criticality. The first stage will be completed in 2017, with a capital budget proposal planned for 2017 to cover the remaining stations.

Given the actions being taken by Hydro, including increased maintenance initiatives after the January 2014 failures, it seems reasonable not to undertake design so as to avoid UFLS in the event of a breaker failure scenario.

6. Shutdown Time for Temporary dc Faults

Lightning strikes to the HVdc OHL usually present the largest source of temporary dc faults. A lightning strike may cause a flashover from the main HV conductor to the tower. Flashovers caused by pollution (salt, smoke and other deposits), combined with partial wetting (*e.g.*, misty rain or fog) also cause temporary dc faults. Temporary dc faults may occur many times each year (10 to 100 times or more on some HVdc schemes).

The converter control system will detect flashover, which will stop the flow of current to the HVdc OHL almost immediately. The HVdc OHL voltage will therefore fall to zero and the arc caused by the flashover will extinguish. After a brief delay (typically 175ms or longer) a converter restart will increase the voltage on the HVdc line to the rated value, in turn restarting the flow of current.

Most lightning-strike induced power interruptions have short durations, with full power resumed in 300 ms, or longer, depending on the time allowed for de-ionization of the arc. However, occasionally the arc will re-strike upon reapplication of the dc voltage. In such cases, the control system will repeat the process of clearing the dc line fault. Typically, a longer time will be allowed for de-ionization during the second automatic fault clearing process. If the second re-start attempt proves successful, the power interruption will have been limited to about 700ms, but UFLS may be required if both poles are affected and the LIL is heavily loaded.

In severe cases (*e.g.*, a flashover caused by a forest fire or by salt fog pollution), a third re-start becomes necessary, in which case the dc voltage is typically lowered to about 80% of the rated voltage. If this re-start is successful, the power interruption will have lasted for at least 1 second, and the power transmission after recovery will be limited to 80% of the rated power. UFLS may be required if both poles are affected and the LIL is heavily loaded.

The converter station control scheme will include all of the necessary features to accommodate all of the re-start steps as outlined above, as part of all HVdc schemes, including HVdc OHL.

None of the studies Hydro provided included cases assuming more than one required re-start attempt. Multiple restrikes are likely to happen, particularly if the de-ionization period is relatively short. If re-strikes happen frequently, then it is recommended that the de-ionization period be extended by 100ms. Re-strikes may cause more UFLS operations. Re-strikes may have an impact on the performance of the frequency of the IIS, and it may be necessary to install additional high inertia synchronous condensers.

a. Conclusions

IV-5. Multiple restrikes are likely, but none of the studies provided by Hydro included cases where more than one re-start attempt proves necessary.

7. Adequacy of the Inertia in the IIS

The preceding sections focus on the major concern of whether the inertia proposed in the IIS will prove sufficient. Effectively, the role of the high inertia synchronous condensers and other synchronous condensers in the IIS is to slow down the fall of system frequency in the event of a trip of one pole, or brief interruption of power delivery on the LIL (*e.g.*, a monopolar or bipolar flashover on the HVdc OHL), or the trip of generation in the IIS.

During the interruption of power supplies, the loads will continue to take power, but insufficient power is fed into the ac network, and the system frequency will start to fall. As the frequency falls the synchronous condensers will slow down, losing part of their kinetic energy[178] as power delivered to the ac network. When the LIL recovers (e.g., after a temporary fault is cleared, or after a single pole trip), or when the LIL ramps up its power to pick up the lost power from a generator in the IIS, the energy balance will be restored, the speed of generators and synchronous condensers increase, and the frequency will return to the nominal value.

The UFLS scheme seeks to protect the ac network from total collapse, and will disconnect loads in the ac network when the ac frequency drops below certain settings. This protection will operate in the case of a bipole trip of the LIL, unless the LIL is operating at low load. The protection may also operate if power recovery on the LIL takes longer than expected. For example, if the LIL is operating at high load in bipolar mode and a temporary fault on the HVdc OHL restrikes one or more times, UFLS is likely to happen.

The response to PUB-NLH-283 includes a study of the impact of extending the restart time after a temporary bipole fault from 200ms. It concludes that with two high inertia 175Mvar synchronous condensers and two other synchronous condensers in service, there would be no loss of load if the time is extended to 250ms. With three 175Mvar synchronous condenser and two other synchronous condensers in service there would be no loss of load if the time is extended to 467ms.

Assuming LIL operation at full capacity with two high inertia 175Mvar synchronous condensers and two other synchronous condensers, and curtailment of the Maritime Link, Hydro has calculated the risk of UFLS with a restart time of 450ms. The following table shows the results of those calculations.

Table IV.5: Annual Risk of Under Frequency Load Shedding Assuming a 450 msec Restart Time on the Labrador-Island HVdc Link

Year	Exposure Hours	% of Year
2018 - 2028[1]	0	0
2029	7	0.08

[178] The kinetic energy depends on the rotating mass and the square of the rotational speed.

2030	16	0.18
2031	34	0.39
2032 - 2041[2]	36	0.41

Notes:
1. LIL deliveries at Soldiers Pond do not exceed 779.5 MW over peak. Reserves met by combination of LIL, Island hydro-electric, and combustion turbine.
2. LIL deliveries capped at 830 MW in this period with additional capacity and reserve requirements met by addition of on Island combustion turbine.

The table demonstrates that the risk of UFLS increases with time, likely linked to an increase in load in the IIS, and therefore of higher import on the LIL. Hydro could reduce the risk through additional high inertia synchronous condensers.

The time required for de-ionization depends on many factors (including weather and other environmental conditions). Consequently, a de-ionization time of, for example, 175ms may prove sufficient most of the time, but not on occasions when conditions would permit a re-strike to occur.

Hydro has stated that:[179]

> "*It is anticipated that all synchronous condensers will be in operation throughout the daily peaks during the peak load season. At night when the Island Interconnected System and ML loads are reduced, it is anticipated that one of the five synchronous condensers will be removed from service to reduce system losses.*"

During early operation, a restrike may not have a significant impact on the IIS (because the LIL will not be loaded to capacity). However, as the IIS load increases and as island generation is retired, the rate of fall of frequency will increase, and restrikes could result in the need for significant UFLS. If restrikes occur frequently and perhaps require restarting at reduced dc voltage, it is likely that more inertia and potentially more generation resources could be required. In practice, the question concerning adequacy of the inertia provided will only be fully answered after gaining considerable operating experience.

8. Comments on the Studies

The studies show that, based on Hydro's underlying assumptions, it is possible to avoid UFLS during all the studied fault conditions, apart from:

- A bipole trip
- A trip of a pole, when operating in monopolar mode
- Trip of IIS generation, if the LIL is fully loaded
- AC faults close to Bay d'Espoir
- AC breaker faults at the converter station

The ac busbar faults at Bay d'Espoir prove particularly onerous, because they result in a rapid decrease in the ac network frequency and in some cases a trip of the LIL. Hydro considers faults

[179] PUB-NLH-271

at Bay d'Espoir to be "exceptional," and UFLS acceptable in the event of these rare faults. UFLS has been accepted so far for faults at the Bay d'Espoir ac busbar.

However, the dynamics of the ac network will change significantly post LIL and the Maritime Link. PUB-NLH-564 provided study results by GE Grid, based on a detailed control model for the LIL and using the ABB model for the Maritime Link. This study indicates that the faults at Bay d'Espoir would not result in angular instability, or unacceptable ac voltages, using the optimized control parameters. It is not clear from the information provided whether spinning reserves were provided by the LIL, by generation in the IIS, or by a combination of the two. The location and split of the reserve may have a significant impact on the study results, because the ability of the LIL to support the ac network is limited if it is operating at maximum power at the time of the fault. The studies remain on-going, and therefore subject to confirmation.

The main question here is whether the ac busbar faults at Bay d'Espoir should still be permitted to result in instability or UFLS, given that:

1. The fault could result in a bipolar outage, with attendant, extensive UFLS.
2. There seem to be a relatively simple solution to the problem (the provision of one additional high inertia synchronous condenser).
3. Providing additional high inertia synchronous condensers will make the IIS more robust (*e.g.*, able to withstand restrikes on the HVdc OHL).
4. Hydro may wish to become compliant with the NERC design criteria.

Hydro should pursue this issue. Given the need to avoid commutation failures during fault recovery at Soldiers Pond, voltage dependent converter recovery control may be required. Voltage dependent recovery is a special converter control mode that monitors the ac voltage amplitude, and if the voltage is lower than 80%, the rate of increase of the dc current is slowed down. This situation would result in a slower recovery of power. Additionally, HVdc OHL faults may take longer than 175ms to de-ionize (as the studies assumed), resulting in re-strikes of the fault. The overall result of these factors is that the power infeed may remain below the system load for a longer duration, resulting in a larger drop of system frequency, with resulting risk of UFLS.

The responses to PUB-NLH-481 and 482 discuss mitigation strategies to avoid UFLS on the IIS when the LIL is in monopolar operation. These strategies include trying to avoid operating at high load, in order to permit the LIL to provide emergency support in the event of a trip of generation in the IIS. However, Hydro states that during late fall, winter and early spring there may be insufficient generation on the island to supply all island loads without power import from the Maritime Link.

The benefit of curtailing the Maritime Link is substantial. The response to PUB-NLH-444 states that, when operating the LIL at rated power with the Maritime Link in service (and therefore able to be curtailed), it requires 2 high inertia synchronous condensers at Soldiers Pond, with 3 needed when the Maritime Link is not in service.

The studies conclude that the response time of the IIS generation is too slow to respond to the loss of the IIS generation. Therefore, Hydro intends to operate with reserve in Labrador; it will, in other words, use the LIL normally at less than its full rating, in order to preserve the ability to automatically increase the power import very quickly, by the HVdc frequency controller.[180,181] In particular, with the Maritime Link out of service, Hydro intends to limit the power delivered to the IIS via LIL to 662 MW (the continuous import capacity of a single LIL Pole).

9. Other Required Studies

Many important studies remain to be completed, including:

- Joint study with NSPI and NBP concerning emergency assistance and reserve sharing (PUB-NLH-501, 525, 593)
- Exchange of PSCAD models of the LIL and Maritime Link (PUB-NLH-510)
- Interaction studies between the Maritime Link and the LIL (requires PSCAD models) (PUB-NLH-524)
- Benchmark studies of the PSS/E models of the Maritime Link and the LIL (requires PSCAD model) (PUB-NLH-530)
- Studies investigating solutions to Bay d'Espoir instabilities (PUB-NLH-511, 564)
- Frequency controller study for the Maritime Link (PUB-NLH-521)
- Settings for future UFLS scheme (PUB-NLH-527)
- Small signal study (requires PSCAD models)
- Systems studies to determine sharing of reserve between LIL and IIS generation (PUB-NLH-564)
- HVdc OHL Restrike studies (PUB-NLH-568)
- New Operational Procedures and associated System Studies

10. Conclusions

IV-6. AC faults at Bay d'Espoir lead to UFLS, but Hydro has generally dismissed them as "exceptional".

IV-7. Numerous studies remain to be completed; their expeditious completion is essential.

C. System Reliability

1. Overall LIL Reliability

Hydro summarized overall predicted reliability of the LIL in the response to GRK-NLH-060, which the following table summarizes.

Table IV.6: Composite Island Link Bipole Reliability

Modification to PUB-NLH-212 Attachment 2 Table 3-2: For Labrador - Island HVdc Link Converter Bipole Failure

[180] The HVdc frequency controller will monitor the frequency in the IIS and will increase the power import if the ac frequency falls and will decrease the power import if the ac frequency increases.
[181] PUB-NLH-447 and 486

Element	Failure Rate (f/yr.)	Repair Time (hrs.)	Downtime (hrs./yr.)
Bipole – Muskrat Falls	0.05	0.13	0.007
Converter Pole + Converter Pole – Muskrat Falls	0.0084	6.86	0.057
Bipole HVdc L1 (Labrador) – 388	0.074	24	1.776
Pole 1 + Pole 2 (submarine cables)	0.007	621.7	4.479
Bipole HVdc L2 (Island) – 680 km	0.13	24	3.12
Converter Pole + Converter Pole – Soldiers Pond	0.0084	6.86	0.057
Bipole - Soldiers Pond	0.05	0.13	0.007
Total	0.3278	683.4	9.503

The data for the converter station in the original table in the report titled *Reliability & Availability of the HVdc Island Link*[182] used the bipole failure rate of 0.24 per terminal, which was recommended by Manitoba Hydro, rather than the 0.05 value used in the revised table. The failure rate guarantee is 0.10 per year for the converter stations at the two ends, but a number of exclusions apply to this outage rate. Furthermore, the relatively easy evaluation criteria for the converter station should also be considered when making the overall prediction. The use of the original value increases the bipolar outage rate to 0.7078 per year (more than 2 outages in a 3-year period).

Table IV.7: Reduced Power Capability Modes

PUB-NLH-212 Attachment 2 Table 3-3: Reduced Power Capability Modes			
Element	Failure Rate (f/yr.)	Repair Time (hrs.)	Downtime (hrs./yr.)
Converter Pole – Muskrat Falls	1.64	13.8	22.42
Pole 1 HVdc	2.04	6.3	12.87
Pole 2 HVdc	2.04	6.3	12.87

[182] Reliability & Availability of the HVdc Island Link, SNC-Lavalin, 10 Apr-2012, PUB-NLH 212, Attachment 2.

Converter Pole – Soldier's Pond	1.64	13.8	22.42
Total	7.36	40.2	70.58

The data in the original table in the report titled *Reliability & Availability of the HVdc Island Link*[183] included the annual outage time for maintenance of three days for each pole, giving an outage time of 144 hours, bringing the total downtime to 214.6 hours. Maintenance outages can be scheduled to take place at times of low load in the IIS; therefore, their impact will be much less significant than forced outages. The omission is acceptable when estimating the Forced Outage Rate; however, Hydro has chosen to use the lower value of the pole outages given in the original report, rather than the higher number of pole outages (five per pole) from the guarantee.

The Forced Outage Rates (shown in the next table) result from combination of the previous two tables.

Table IV.8: Combined – Forced Outage Rates

Element	Downtime (hrs./yr.)	Forced Outage Rate (%)
Converter Pole – Muskrat Falls	22.48	0.26
Bipole HVdc L1 (Labrador) – 388 km	11.13	0.13
Submarine Cables	4.479	0.05
Bipole HVdc L2 (Island) – 680 km	19.51	0.22
Converter Pole – Soldier's Pond	22.48	0.26
Total	80.1	0.91

In summary, Hydro's revised data indicates that a bipole outage should be expected approximately every 3 years (.3278) with an average duration of about 29 hours (9.503 hours per year). The converters and the HVdc OHL make the largest contributions to the number of outages. The largest contributions to the outage time are the HVdc OHL and the HVdc cable (in spite of the low predicted failure rate of the HVdc cable).

The "reduced power" table above indicates that single pole outages, with associated reduction of power delivery capability, should be expected approximately 7.3 times per year, each with an average duration of about 9.6 hours. Outages associated with the electrode lines and the dc switching stations have not been considered in this analysis, and would slightly increase the number of outages.[184]

Also, Cigre's definition of a bipole outage differs from Hydro's definition, as Hydro includes in its definition the failure of a pole when in monopolar operation. Section 4.8 of Cigre Technical

[183] Reliability & Availability of the HVdc Island Link, SNC-Lavalin, 10 Apr-2012, PUB-NLH-212, Attachment 2.
[184] PUB-NLH-541

Brochure 590 “Protocol for Reporting the Operational Performance of HVdc Transmission System” states the following:

> *For reporting purposes, bipolar outage is one in which both poles are lost as a direct or immediate consequence of a single event. Since such bipole outages are of special significance, it is requested that a narrative discussion of every bipole outage be included in the discussion section of the report. The discussion should indicate whether both poles tripped simultaneously, and if not, the sequence of events involved. Overlapping pole outages due to different events or with a prior outage of the other pole should be reported as separate pole outages, not as a bipole outage.*

Notwithstanding Cigre’s definition of a bipole outage, Hydro stated that the Reliability Requirement section of the contract includes the statement:[185] “If the first pole is out for maintenance or repair and an event occurs that causes an outage of the second pole, this is considered as a bipole forced outage”. The response to PUB-NLH-574 clarified this issue by explaining that long duration pole maintenance outages would be scheduled at times of low loading requirements on the LIL. Furthermore, the probability of the second pole’s failing shortly after the failure of the first pole (but not at exactly the same time) would be very small and may not significantly change the overall number of bipole outages.

It is not possible to forecast the number of outages (bipolar or monopolar) with substantial accuracy. The number of equipment failures depends on the quality of the design, manufacture, and maintenance of the equipment, and on the stresses to which it is exposed. The general tendency is for a higher number of failures in the first couple of years of operation, with the number then settling down to a lower level for many years, until aging causes the number of failures to increase again.

2. Teshmont Probabilistic Based Transmission Reliability Assessment

On May 27, 2016, Hydro provided a report by Teshmont Consultants LP, entitled “Probabilistic Based Reliability Assessment – Island Interconnected System.” This Teshmont report appears to have been completed in large part in 2014. The report assessed the reliability assumptions that had been provided by Hydro, which generally included higher outage rates for the converter stations than Hydro has assumed in the more recent calculations, e.g. the original data provided in PUB-NLH-212, Attachment 1. Teshmont found the reliability data provided by Hydro for the study generally reasonable, apart from repair times for HVdc OHL failures, which are much lower than those in the CEA statistics.

The study looked at N-1 and N-2 contingencies, including outages of Holyrood generators, ac transmission lines on the Avalon and LIL bipole outages. The studies were performed for 2017; *i.e.*, prior to the LIL’s entering service, and for 2018 (assumed to be after the LIL entered service). Studies for later years with higher loads in the IIS were not performed. The system study conditions and criteria were the same as for the dynamic performance studies reported in Section B above. The studies evaluated the expected unserved energy (EUE) for the different

[185] PUB-NLH-573

cases, using 300 MWh as the benchmark, which Hydro advises is the same as the LOLH criteria of 2.8 hours.

The pre-HVdc case showed that for the loss of both Holyrood Unit1 and Unit2 (the worst performance) the EUE would be 16,000 MWh/year, using the reliability data provided by Hydro for the Holyrood generators.[186] The worst case loss of ac transmission lines produced an EUE of 100.8 MWh/year, with TL208 and TL242 contributing respectively 41.43 and 58.03 MWh/year, and with the remainder made up of double contingency ac line outages. Upgrades will avoid the outages of TL242, as their impact was an overloading of TL218.

For the post HVdc case (2018) no EUE resulted from generation outages. ac transmission line outages resulted in an EUE of 41.94 MWH/year, most of which came from outages of the radial TL208 ac transmission line. The study also showed no EUE in the event of a bipole trip, provided that the Maritime Link was in service and could provide 300 MW import to the IIS. However, if the Maritime Link is not available, the EUE would be 2720 MWH/year. This shows the importance of the Maritime Link (and its yet-to-be demonstrated supply capability) to the reliable operation of the IIS.

Table 23 from the Teshmont report shows the generation in the IIS and its dispatch and reserve pre and post HVdc, and is summarized below.

Table IV.9: IIS Generation, Dispatch, and Reserve – Pre- and Post HVdc

Generating Unit	Type	Capacity (MW)	Dispatch Pre- HVdc (MW)	Reserve Pre-HVdc (MW)	Dispatch Post-HVdc (MW)	Reserve Post-HVdc (MW)
Bay d'Espoir 1	Hydro	76.5	65.4	11.1	67.7	8.8
Bay d'Espoir 2	Hydro	76.5	65.8	10.7	67.7	8.8
Bay d'Espoir 3	Hydro	76.5	65.8	10.7	67.7	8.8
Bay d'Espoir 4	Hydro	76.5	65.8	10.7	67.7	8.8
Bay d'Espoir 5	Hydro	76.5	65.8	10.7	0	76.5
Bay d'Espoir 6	Hydro	76.5	65.8	10.7	0	76.5
Bay d'Espoir 7	Hydro	154.4	154	0.4	154	0.4
Cat Arm 1	Hydro	67	63.5	3.5	63.5	3.5
Cat Arm 2	Hydro	67	63.5	3.5	63.5	3.5
Upper Salmon	Hydro	84	84	0	84	0
Hinds Lake	Hydro	75	75	0	75	0
Granite Canal	Hydro	40	40	0	40	0
Paradise River	Hydro	8	8.0	0	8	0
Exploits River 4	Hydro	24	24	0	24	0
Exploits River 5	Hydro	4.5	4.5	0	4.5	0
Exploits River 6	Hydro	4.5	4.5	0	4.5	0
Exploits River 7	Hydro	4.5	4.5	0	4.5	0

[186] The outage rate used by Hydro for the Holyrood generators was 3 times higher than the CEA reliability data.

Exploits River 8	Hydro	4.5	4.5	0	4.5	0
Exploits River 9	Hydro	30	27	3	27	3
Exploits River	Hydro	18	18	0	18	0
Holyrood 1	Thermal	170	170	0	Standby	0
Holyrood 2	Thermal	170	170	0	Standby	0
Holyrood 3	Thermal	150	150	0	Sync. Cond.	0
Holyrood CT	CT	120	100	20	0	120
Stephenville	CT	50	0	50	0	50
Hardwoods	CT	50	0	50	0	50

In the post-HVdc case, Teshmont assumed that the Maritime Link would instantly change from export of power from the IIS to import of 300 MW of power to the IIS, but this is likely to be unacceptable to the Nova Scotia power system. Additionally, the loading of 10 generators could be increased and an additional five generators could be started in this scenario, to provide an additional 424.4 MW of generation capacity. The Hydro generation is not fast enough to prevent UFLS, but its duration might be quite short, perhaps as short as 1 hour, provided that all generation was available. Therefore, the EUE resulting from a bipole trip would not be zero.

The value of the Teshmont analysis is somewhat limited in that studies were not performed for later years, when reserve margins would be smaller because of projected load increases. The report does show that the reliability would have been better in 2018 with the LIL and the Maritime Link, and after the retirement of units 1 and 2 at Holyrood. Without the Maritime Link, the performance is worse than the present criterion of a EUE of 300 MWh.

3. Conclusions

a. Pole Outages

IV-8. The LIL and the associated high inertia synchronous condensers have been designed to allow LIL operation to minimize the need for UFLS in the event of monopolar outages and temporary interruptions.

IV-9. Pole outages are estimated by Hydro to occur on average 9.36 times per year.

IV-10. There will likely be significantly more pole outages than predicted by Hydro.

This might especially be the case in the first few years of operation. Because of the bipolar design, the occurrence of more pole outages than predicted will not necessarily result in additional UFLS operations because the following actions will happen:

- The high inertia synchronous condensers will slow down the fall of the system frequency, by delivering power to the IIS.
- If one pole trips, the other pole will increase its power, to a maximum of twice the rated direct current for 10 minutes, after which it will be gradually reduced to 1.5 times the rated direct current.
- When in service the Maritime Link will be curtailed immediately in the event of a pole trip, thereby effectively reducing the loss of power infeed from Muskrat Falls.

- Standby generation will be started, so that the reduction of the direct current from twice to 1.5 of rated current will not result in UFLS in the IIS.
  - If some of the offline generation fails to start, then there could be a need for UFLS.

These measures have been included in the specification for the HVdc scheme, in order to reduce the number of UFLS operations that would otherwise have had to be implemented.

IV-11. The Maritime Link is critical to the reliability of the IIS power supply

If the ML is not in service, Hydro plans to operate the IIS with sufficient spinning generation reserve so that the loss of one pole will not result in UFLS in the IIS. Hydro will develop these operating restrictions in 2016.

b. Bipole Outages

IV-12. In the event of bipolar outages, UFLS may take place.

UFLS will be avoided if the loads in the IIS can be picked up immediately by generation in the IIS and the dropping of export on the Maritime Link to Nova Scotia. Operating the IIS with such high levels of reserve at all times is unlikely to be economically justified, because of the relatively low, but not insignificant probability of a bipole trip.

IV-13. Hydro considers acceptable the occurrence of UFLS as a consequence of a bipole outage.

Hydro does so because the IIS is an island system with limited interconnection to other ac networks, and the power delivery system is designed to provide the most economical design with acceptance that some rare faults will result in UFLS. This design approach for bipolar outages is also supported by NERC.

IV-14. The ability of the yet-to-be defined UFLS scheme to prevent system collapse after a bipole trip is of critical importance and hence makes the development of a successful scheme a high priority.

V-15. Hydro estimates the average number of bipole outages to be 0.10 for the converter stations and 0.22 for the HVdc OHL, giving a total of 0.32, i.e., a bipole failure about every three years.

IV-16. Hydro considers under-frequency load shedding acceptable when a second fault happens while the LIL or the ac network is already in an N-1 condition (*i.e.*, an earlier fault has not yet been rectified).[187]

IV-17. It is likely that Hydro has underestimated the potential number of bipole outages.

This underestimation exists because:

1. The number of bipole outages for the converter station has not been based on the Cigre data (which indicated 0.24 bipole outages per year), but on the manufacturer's

[187] PUB-NLH-482

guarantee, which is somewhat irrelevant because the evaluation process makes it too easy to pass, regardless of the failure rates "guaranteed."

2. Other causes of outages of the LIL or interruptions of power infeed to the IIS from Muskrat Falls, which have not been taken into account include:
   a) Tripping of some or all ac lines leading to the Muskrat Falls converter station.
   b) Tripping of some or all ac lines leading to the Soldiers Pond converter station.
   c) Delayed clearing of faults in close proximity to the Muskrat Falls or Soldiers Pond converter stations (*e.g.*, because of protection or breaker failure).
   d) Major faults (*e.g.*, latent defects, fire or extensive insulation damage to 2 or more high inertia synchronous condensers) requiring major repair at times of high loading on the LIL.
   e) Operator errors.
   f) Major fires in the converter stations.
      i) Bullets a, b, c, and e above will result in UFLS, but probably of relatively short duration
      ii) Bullets d and e above could result in longer periods of reduction in power transmission on the LIL.
      iii) Hydro and the HVdc manufacturer have taken reasonable steps in the design and implementation of the converter station to minimize the risk of fires.
3. Furthermore, the estimate of the number of bipole outages does not include faults at the HVdc cable switching station or the electrode line conductors.
   a) Hydro has not provided an estimate of the average number of bipole faults that may be caused by events in the HVdc switching station. We expect that the number would be very small, e.g., below 0.02 per year.
   b) Electrode line failures are estimated to occur 2 times per year. Most electrode line failures will not cause a bipole outage. However, some may do so because the HVdc system is vulnerable to a pole trip becoming a bipole trip when the scheme is operating with a single electrode line conductor.
4. Hydro has classified faults on the second pole before the first pole failure has been repaired, as a bipole failure. This is not in accordance with the Cigre definition.
   a) The additional contribution to the bipole outage rate of this event is likely to be very small if adequate spares provisions and qualified and trained fault finding and repair personnel is located close to both converter stations.
   b) Hydro has stated in responses to RFIs that they will revise their operational procedures for the ac network after the LIL becomes operational.[188] In particular, they have stated that when operating with a single pole in service they will endeavor to minimize the power import on the LIL to a level where there would be no UFLS in the event of a trip of the remaining pole. However, the response to PUB-NLH-522 states:

      Hydro cannot confirm, nor guarantee, that the Island Interconnected System will not experience under frequency load shedding following the loss of the

[188] PUB-NLH-481 and 482

remaining pole when operating in monopolar mode under all system loading conditions. . . . With the LIL operating in monopolar mode, its sudden loss of delivered power from Labrador must be made up by the available generation on the Island. If the loss of supply from Labrador exceeds the capabilities of the on Island generation, under frequency load shedding must be employed to avoid system collapse. During peak load conditions there will be insufficient generation to supply the entire load on the Island. With the LIL operating in monopolar mode during peak load periods, loss of the LIL must result in under frequency load shedding to restore system frequency.

4. Recommendations

Recommendation IV-1. Hydro must clearly ensure the use of the best design and construction practices for the electrode lines, because they have significant potential for causing bipole outages.

Recommendation IV-2. Hydro and its converter station contractor should perform transient stability studies with multiple restart attempts for HVdc OHL faults.

The results of such studies may have an impact on the design of the UFLS scheme.

Recommendation IV-3. Re-strike performance should be continuously monitored and recorded.

If restrikes contribute significantly to the number of UFLS operations, then it may be desirable to adjust the de-ionization time and/or to install additional high inertia synchronous condensers.

Recommendation IV-4. Hydro should undertake an investigation of ac faults at Bay d'Espoir, to determine what steps could be taken to minimize the impact of such faults.

Recommendation IV-5. Hydro should make space provisions for the installation of a 4th high inertia synchronous condenser near Soldiers Pond.

This reservation would facilitate the future addition of an additional high inertia synchronous condenser, if early operating experience indicates that the need for more inertia to ensure acceptable system operation.

Recommendation IV-6. Hydro should include the complete plan for remaining studies on the Transition Team's integrated schedule, and monitor completion performance.

Recommendation IV-7. Hydro should take into account in its planning of the standby and reserve power capability of the IIS, the potential occurrence of the fault types mentioned in Conclusion IV-17.

A relatively low failure rate for each of these events would be reasonable.

Recommendation IV-8. The performance of the LIL should be rigorously monitored and recorded, using procedures such as those provided in Cigre Technical Brochure 590.

The data should be analyzed by the asset management team and the generation planning team. These analyses should feed into the asset management plan and into the forward planning of future generation resources.

Recommendation IV-9. While loss of load on a bipole trip will be necessary, Hydro should study options, such as operating limits, to reduce incidents of UFLS.

Recommendation IV-10. While UFLS will be necessary in the event of most bipole trips, their impact on customers should be reduced by Hydro ensuring that sufficient generating resources and/or guaranteed power via the Maritime Link are available to be brought on line to meet the power demand of the IIS during a bipolar outage of LIL.

Recommendation IV-11. The critical role of UFLS in preventing system collapse on a bipole trip requires that development and implementation of the UFLS scheme receive a high priority as well as suitable oversight by the Board.

V. Power Supply Adequacy and Reliability Post - Muskrat Falls

A. Background

In this phase of the investigation, Liberty reviewed the adequacy and reliability of supply after the interconnection of the IIS to Muskrat Falls. Many analyses have been completed, with more still to come, and much has been written about the reliability of the IIS and its components in the years ahead. This technical material which is discussed in Chapters III and IV, is essential and is necessary in designing the new system. When the detailed analyses are done, however, the remaining questions of customers and other stakeholders are very simple:

- How often will the lights go out from system-related failures?
- Is that frequency of outages acceptable?

The nature of the IIS system, and specifically its size in comparison to the LIL, makes loss of load on a bipole trip inevitable. Further, considering the harsh environment through which the OHL runs, a bipole outage of days, or even weeks, from tower failures is not an unreasonable expectation. This risk of extended outages for events which Hydro considers a low probability, such as an extended bipole outage, needs to be addressed.

Moreover, when this concern on reliability after the interconnection with Muskrat Falls is considered along with the concerns on reliability prior to the interconnection as discussed in Chapter II, the inevitability of the need for new generation in the future is apparent. The question is rapidly transitioning from whether the IIS needs more capacity to how much and when.

B. Findings

1. UFLS

The most likely outage impacts on customers arise from under-frequency load shedding (UFLS). UFLS is automatic and instantaneous, in that it is triggered when supply becomes insufficient to meet the demand.

Hydro has experienced UFLS perhaps 5-10 times per year in recent years. This has happened when a perturbation, perhaps the trip of a generating unit, cannot be responded to quickly enough to prevent a degradation of frequency. This phenomenon is a characteristic of the present IIS. With the LIL in service, the IIS will be stronger and should be able to respond quickly to such relatively minor disturbances. Accordingly, this variety of UFLS that has regularly been seen in the IIS in the past should be significantly reduced with the LIL operating. On the other hand, the various analyses discussed in this report define new scenarios in which UFLS can be triggered.

Liberty in its past reports has expressed concerns about Hydro's operating culture that appears to tolerate outages more than other utilities. This may, at least in part, stem from the past inevitability of UFLS in the IIS. This is not the case elsewhere, where UFLS is very unusual, and represents a significant system failure. The following table, for example, shows the number of UFLS events and the associated MW as reported by NERC. In the 11-year period, two reliability regions had no incidents of UFLS, and three had only one. In four of the 11 years, there were no incidents in any of the regions, and in nine of the 11 years, there was only one or less.

Figure V.1: Activation of Under Frequency Load Shedding[189]

ALR2-3 Activation of Under Frequency Load Shedding

Year	FRCC	MRO	NPCC	RFC	SPP	SERC	TRE	WECC
2003			17644	6105			1549	
2004			24					
2005								
2006								
2007		486						
2008	1273		48		673 (2 Events)			
2009								
2010								
2011				176				
2012			115					
2013			2000.5					

The IIS has become used to UFLS in the past, but it should be recognized that it is intended as the last resort to prevent a total system failure and hence is rare in a modern system. It is not a feature to which one should grow accustomed. The goal for a modern system is no incidents of UFLS with the recognition that perhaps once in ten years is an inevitable, and acceptable, risk. The above table suggests a one in 7.3 years average per region, but if NPCC is eliminated, it becomes one in 11 years.

The frequent references to UFLS in this report and Hydro's various analyses are troubling and raise concerns. Stakeholders can and should question the degree to which UFLS is being considered to respond to operating conditions after the interconnection with Muskrat Falls.

Notwithstanding the undesirability of UFLS, the reality is that the IIS is a relatively small system for an injection the size of the LIL. A permanent[190] outage of the bipole, unless it is carrying very limited load, will not be able to be picked up quickly enough, if at all, by on-island generation and tripping of the Maritime Link. The inevitable result is UFLS. The studies indicate a probability of a bipole outage every three years with an average outage time of 29 hours.

2. Manual Load Shedding (aka Rotating Outages)

The need for a utility to manually drop load is rarer. Manual load shedding takes place on a planned and deliberate basis over a period of time. Typically, the operator is tracking load as it increases and anticipates that supply will soon be unable to meet the load. Operators have preplanned steps to drop load as appropriate and to minimize customer impact by restoring those dropped after a short period and dropping others.

Rotating outages were called upon in both 2014 and 2015 in the IIS. With the near-term supply vulnerability to the interconnection before Muskrat Falls, this could be required again. The probability of such manual load shedding will reduce significantly after Muskrat Falls and the LIL are in service.

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[189] ALR2-3 is NERC's metric for UFLS. This table was published by NERC at http://www.nerc.com/pa/RAPA/ri/Pages/UnderFrequencyLoadShedding.aspx

[190] A "permanent" outage of the bipole simply means an interruption that is more than momentary.

3. Widespread Blackouts

Needless to say, automatic and manual load shedding are intended to prevent widespread blackouts, but they can still occur. Such a situation occurred in both 2013 and 2014 in the IIS. To the extent that both incidents were not supply related, it is not clear that they would have been avoided in a post-Muskrat Falls system, although the new system will be more resilient.

4. Vulnerability to Post-Muskrat Falls/LIL Outages

The possibility of both rotating and widespread blackouts in the post-Muskrat Falls environment is lower than the existing situation. The new system, however, as resilient as it may be, will not protect against poor operating practices or decisions. Equipment failures and plant operating problems on Hydro's system contributed to the outages and consequences of 2013. Weak maintenance and emergency response practices by Hydro contributed to the outages of 2014. Poor operating and reliability practices by Hydro were the primary cause of the 2015 outages. The significant investment in Muskrat Falls will help the system to respond to such events, but it will not alone prevent them.

The threats to reliability can be considered to come from two causes: (1) the generally manmade problems, such as those that happened in 2013-15, and (2) the system design related issues, as discussed in this report and Hydro's many technical analyses. In Chapter VI (Transition to Operations), we examine the challenges facing Hydro in getting ready for the integration of Muskrat Falls with the IIS. In that discussion, we describe why a successful integration is critical to eliminate the manmade problems that plagued Hydro in 2013-2015 and the realization of the Muskrat Falls benefits. This section addresses the system design reliability considerations.

5. Cause and Likelihood of Customer Outages

From a customer outage perspective, permanent bipole faults are of primary concern. A simultaneous failure of both poles is considered N-2 by Hydro and is hence considered an acceptable risk, even though loss of load can result. In addition to the simultaneous failure of both poles, a bipole outage can result in steps, first one pole fails and then, sometime later, the second pole fails. This is an N-1-1 scenario which Hydro believes is also an acceptable risk. In any event, the design results in the likelihood of loss of load on a bipole trip of the LIL under typical loading, and Hydro estimates a bipole trip about once in three years[191] and lasting on average 29 hours.[192]

When a permanent (i.e., more than momentary) bipole trip occurs, it is urgent to shed load as quickly as possible. As we saw in Chapter IV.B.4, UFLS is necessary, and if the UFLS scheme is inadequate, a total collapse of the system is the result. UFLS will interrupt a number of circuits sufficient to hold the system together during this transient, after which the System Operator will take steps to bring on standby capacity and restore the interrupted customers. The bottom line is that a number of customers will have been out of service for perhaps a few hours.

[191] Liberty explained earlier why we believe bipole trips are likely to be more frequent than estimated by Hydro.
[192] Note that while a bipole trip causes UFLS, this does not mean that loss of load is a given for the entire duration of the LIL outage.

It is fair to question the appropriateness of a reliability criterion that permits UFLS at this level. The question is moot, however, since there is no realistic alternative at this time. The size of the IIS in comparison to LIL deliveries is the key feature making UFLS inevitable. The economics of avoiding this are not practical.

It should be noted that the originally contemplated response to a bipole outage was a trip and isolation of the Avalon. The subsequent addition of the Maritime Link allowed this to be changed and results in limited UFLS, which is obviously more preferable than a disconnection of the IIS's major load center.

6. Extended Outages

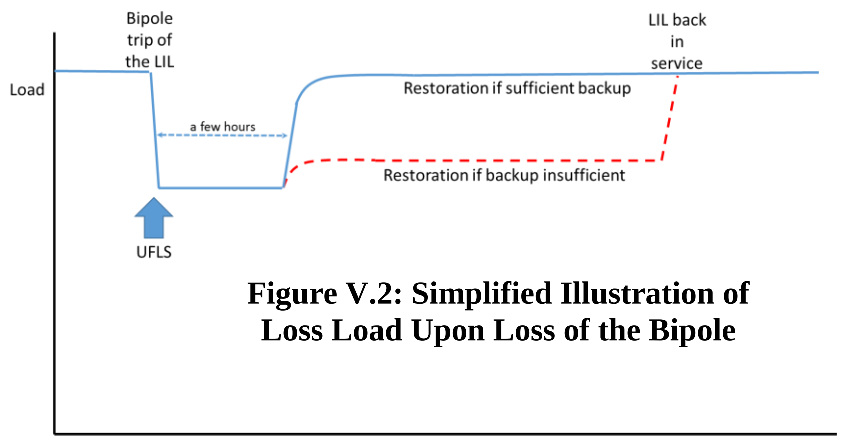


Figure V.2: Simplified Illustration of Loss Load Upon Loss of the Bipole

In the above case of a bipole trip with successful UFLS, the operator was able to bring on backup supply to restore the UFLS-interrupted circuits promptly. But what if the available backup capacity was insufficient? Clearly, all the UFLS-affected load could not be restored. The System Operator would likely then resort to rotating outages, so that the impact on individual customers could be minimized. A new group of customers would be manually interrupted to allow restart of the UFLS-affected customers. This rotating process through many groups of customers would be continued as long as necessary.

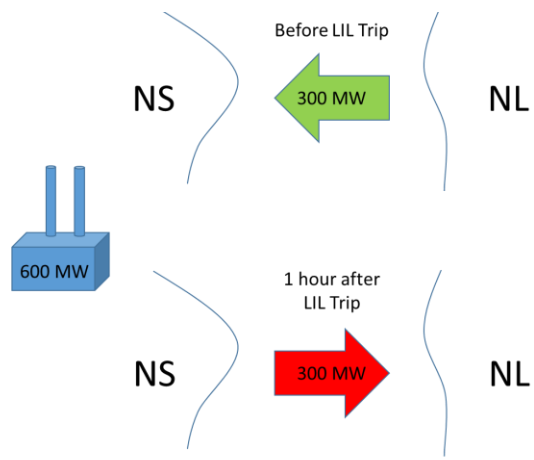
While the UFLS customer interruptions first caused by the bipole trip are inevitable, as we discussed earlier, the subsequent extension of those outages and the evolution through rotating outages should be considered unacceptable. The solution is, of course, to have suitable backup capacity. Note, however, that Hydro considers the bipole trip to be an N-2 event and hence considers the loss of load, by UFLS or any other mechanism, to be acceptable. We agree with the loss of load from UFLS, since there is no choice. But we do not agree that the subsequent extension and rotating blackouts are acceptable.

It is also important to consider another degree of extended outages, and those are of the variety that last many days or weeks as opposed to hours or a day or two, as the IIS has seen in the past (2014 and 2015). Consider, for example, a bipole outage caused by multiple tower failures on the OHL. Multiple tower failures are a real potential as discussed above, despite the measures that Hydro is taking to prevent them. Such an event would cause a lengthy outage of the bipole with the result that, in the absence of adequate backup supply, rotating outages, potentially over several days or weeks, might be required. This is obviously unacceptable, but yet it also carries another threat. If the bipole is out for a considerable time, particularly in the winter, the risks of another contingency grow with time. An unacceptable condition could therefore evolve into a catastrophic scenario.

The key to avoidance of extended outages when the LIL is lost is the availability of adequate backup supply to the IIS. This supply can take the form of new on-island generation and/or imports via the Maritime Link. In this regard, the Maritime Link becomes all-important. Hydro is relying on the Maritime Link to provide 300 MW when necessary. Needless to say, this is a very large reserve, especially considering that Hydro's current reserve requirement on the IIS is 240 MW. Liberty does not believe, however, that the credibility or practicality of this source of capacity has been demonstrated. Until the Maritime Link source is validated, or new CTs provided, the threat of extended outages will be present.

Liberty does not underestimate the benefits of the Maritime Link. The Maritime Link can provide significant benefits to Muskrat Falls and the IIS. There is no question that it enhances reliability for the IIS under all circumstances. It also has further benefits in terms of access to other markets for economy and long term transactions.

Figure V.3: LIL Bipole Trip Impact on ML



One must recall, however, that when the Maritime Link was added to the project, it was intended as a supply *to* Nova Scotia and beyond, not *from* Nova Scotia. During normal operations, several hundred MW may flow to Nova Scotia. With a bipole trip of the LIL, that flow will be interrupted, and Nova Scotia's operators must call on their reserves to cover that loss of supply from the Maritime Link. The Hydro analyses assume that Nova Scotia will be able to provide those reserves to satisfy Nova Scotia's own needs and, at the same time, provide several hundred MW for the IIS.[193] This result requires perhaps 300-600 MW of available firm, dependable capacity on the Nova Scotia side. Whether that level is practical remains to be seen as Hydro negotiates with Nova Scotia to determine what it would take for Nova Scotia to make such a commitment. Such a large amount of backup will come at a cost, which has to be balanced against the risk of an LIL trip, as well as the competing cost of new CTs.

In Chapter II, we suggested that more IIS capacity would be required pre-Muskrat Falls in order to assure an adequate interim power supply. In this chapter, we again see the need for new capacity, but this time in order to mitigate the loss of the LIL. There is a possibility that Hydro's pre-Muskrat Falls solution can serve the post-Muskrat Falls need as well. That will be determined by Hydro in its analyses.

It is hoped that Nova Scotia can provide some or all of this needed supply over the Maritime Link, but this does not appear to be a certainty at this time and no information is available to determine if it would be economic. If Hydro is unable to confirm a dependable, economic supply via the Maritime Link, the time to start development of new generation appears to be now.

[193] Note that this reversing of the flow would not be instantaneous. In favorable circumstances, it might take an hour, during which NL would experience loss of load via UFLS.

7. The Two Big Questions

We can now address the two questions raised above.

a. How often will the lights go out?

If the organizational capability questions discussed in Chapter VI are not fully addressed and successfully resolved by Hydro, future widespread disruptions such as those that occurred in 2013-15 are just as likely after the interconnection with Muskrat Falls as they were before.

If those issues are successfully addressed, the probability of widespread disruptions in the electric system will be significantly reduced, and will be less than in the past. Specifically, incidents of UFLS will be greatly reduced, but the reliability studies that have been done indicate a probability of a bipole outage every three years, so one can still expect UFLS perhaps every three years or more. Note that while the LIL may be out for some time, such as 29 hours, this does not translate into an equal duration customer outage. If sufficient backup capacity is available, any customer outages will be limited to the UFLS that takes place. Accordingly, we would expect that the customers interrupted by UFLS would be back in service within a few hours, regardless of the duration of the bipole outage.

Outages greater than the UFLS, either in terms of number of customers or duration, are unlikely if sufficient backup supply is provided.

b. Is that frequency of outages after the interconnection with Muskrat Falls acceptable?

We explained our opinion on the acceptability of UFLS earlier. Ordinarily, we would not consider UFLS to the extent contemplated by Hydro to be acceptable. We must acknowledge, however, that the decision to accept interruptions upon the loss of the LIL was made knowingly years ago, when the consequences were envisioned to be far greater than today. That decision was embodied in the choice of the size of Muskrat Falls and the LIL in comparison to the load on the IIS. We are unaware of a practical way to change that circumstance at this time; hence, a frequency of UFLS consistent with bipole trips at least every three years should be, and in fact must be, considered acceptable.

We have also stressed, however, that outages beyond the UFLS events (*i.e.*, extending beyond the UFLS-affected customers or lasting more than a few hours), should not be considered acceptable. Such extended outages will be prevented if suitable backup supply is in place, such as through firm dependable capacity from Nova Scotia on the Maritime Link and/or new CTs on the IIS.

C. Conclusions

V-1. Major supply disruptions in the future should be significantly reduced by the combination of: (a) enhanced organizational capabilities as recommended in Chapter VI and (b) the resilience of the new Muskrat Falls system.

V-2. UFLS is a last resort to prevent total system collapse and hence, from planning and design perspectives, the number of instances should be limited.

V-3. The planned deign makes UFLS inevitable on the loss of the bipole, (except perhaps under light load conditions); UFLS can be expected once or more every three years.

V-4. The extent to which Hydro can count on the Maritime Link as a source of dependable backup supply and the competitiveness of such supply versus new IIS generation are far from clear.

V-5. The need for added supply to mitigate loss of load on an extended bipole trip has not been sufficiently considered.

V-6. Numerous factors,[194] both pre and post Muskrat Falls, are emerging, all of which point to the need for new supply, and the collective impact of these factors is the likelihood that new supply is needed sooner rather than later.

D. Recommendations

Recommendation V-1. Hydro should expedite efforts to determine (a) the availability of dependable reserves from Nova Scotia or elsewhere and (b) the competitiveness of those reserves versus new IIS generation.

Recommendation V-2. Hydro should evaluate the degree to which new capacity, via dependable Maritime Link supply and/or new CTs, is required to assure that customer outages due to loss of the bipole are limited to those caused by UFLS and those circuits are promptly (hours) restored.

Recommendation V-3. Hydro should prepare a new resource plan that, as necessary, includes new CTs and the dependable portion of any Maritime Link imports, and addresses all of the supply-related risks currently confronting Hydro.[195]

[194] Supply assessment reliability violations, Muskrat Falls delays, uncertainty of Maritime Link reserves, loss of load from extended LIL bipole failure, potential need to replace Hardwoods and Stephenville, further exposure at Holyrood.

[195] Hydro currently has a post-MF supply assessment underway with expected completion in 2016.

VI. Transition to Operations

While the in-service date of Muskrat Falls is still in the future, Hydro is now planning the transition to operating with the new interconnected system. Once the new system is operating, Hydro will have to be a very different company than it is currently. Accordingly, the transition challenge is a significant one and the future reliability of the system will be highly dependent on Hydro's success in responding to that challenge.

Through its various engagements for the Board, Liberty has observed Hydro's management and operations for more than two years. We have learned the unique challenges Hydro faces and have come to understand its fundamental approaches and, equally important, the underlying organizational and operational culture that guides its actions and results. In past reports, we have made both positive and negative observations in this regard. Hydro has responded to our observations in various ways and has been generally constructive in responding.

We have considered the relevance of our prior recommendations in assessing the changes required for Hydro to successfully operate the Muskrat Falls interconnection and effectively become the "new' company that it must become. We have also examined how our prior findings and recommendations relate to Hydro's ability to make the transition to that new company with the necessary new skills. We conclude that our past conclusions remain valid and are as important as ever in the context of the requirement for significant operational and cultural changes. We are also of the opinion that Hydro started its transition with significant handicaps which require urgent attention.

A. A New Company?

We believe that Hydro will become a very different company in the years ahead. Hydro faces much more than a normal, evolutionary change. The coming upheaval features three near-simultaneous large scale events: (a) a large new generation source, (b) the introduction of HVdc technology new to Hydro, and (c) the interconnection of the IIS with other electric systems in North America. Each of these three defining characteristics carries its own opportunities and challenges; and in the aggregate, they will combine to change Hydro on a grand scale.

Muskrat Falls will change the nature of Hydro's generation portfolio considerably. It represents a large source of energy, and allows Hydro to retire the Holyrood thermal units, which are old, high cost, and increasingly unreliable. This major shift in Hydro's power supply portfolio sets the stage for more reliable generation. At the same time, the high construction costs of Muskrat Falls and its associated transmission will influence Hydro's financial structure for decades, with the large increase in rate base causing a substantial impact on what customers pay. This factor also has the potential to limit Hydro's financial flexibility in the future to an as-yet undetermined extent. These questions are crucial to future operation and of paramount interest to stakeholders. They are, however, outside the scope of this report. We do observe that the topics require timely treatment, to permit their inclusion in planning the transition (which we do address), and to assure the financial strength of Hydro to maintain a reliable system. In addition, the location of the new units some 1,100 km from the province's major load center, introduces unique technical and operating challenges. In summary, Muskrat Falls will change considerably the company's generation profile, its financial and rate profile, and its operating practices.

The HVdc technology, although in increasing use throughout the world, has only penetrated North American systems to a limited extent. The technology is totally new for Hydro. In addition to the intrinsic technical challenges, the manner in which the new technology is being applied also creates special challenges. The delivery of a large amount of supply to a single point on a relatively small electric system is somewhat problematic from stability and reliability perspectives. Hydro therefore not only faces the challenges of a new technology, but also special challenges in the way that new technology must be applied. This requires additions to the company's levels of technical expertise and a heightened need for strong and sophisticated operating skills.

The third major event is the pending linkage of the IIS with the North American grid. This linkage has far-reaching consequences, including opening the door to new opportunities. Sales to neighboring provinces and into New England will become possible. Access to power from the neighboring provinces also becomes possible and can improve the reliability of the IIS, while also reducing the amount of reserves required. The economic and reliability benefits offered by the Maritime Link can be substantial, but the required business relationships must be conducted effectively to optimize these potential benefits while managing risk. As an isolated system, Hydro has had limited need in the past for the kinds of business skills now needed, including market knowledge, bulk power transactions, trading, and risk management.

A central question here is how the interconnection transactions will be managed and to whom the benefits (and risks) of such transactions accrue. Specifically, it is critical for Hydro and its customers to understand the degree to which such transactions contribute to the revenue requirement, if at all, and therefore whether or not they influence rates. Such determinations are outside the scope of this report and we therefore offer no opinion on how export and import transactions might be treated. We nevertheless raise the topic because the answer to this question will dictate the kinds of skills and resources required by Hydro and the degree to which market skills must be developed during the transition. Management of potential conflicts between marketing and operations is also a concern. With the Maritime Link only about a year away, such issues should be resolved now.

It is Liberty's opinion that the pending changes are so far-reaching and significant that they will substantially alter the identity of Hydro and influence most of its internal organizations. Such a degree of change is rare, but not unprecedented, in the utility industry.

B. Responding to Change

It would be a fundamental error to think changes as great as those discussed above can be absorbed easily, or with a business-as-usual mindset. Our experience teaches that utilities time and again fail this test to implement significant change. At an intellectual level, they understand the importance and magnitude of such changes and are able to articulate that sensitivity well. But at a practical level, they often make the mistake of thinking that the existing people, systems, approaches, and processes, with perhaps a little fine tuning, can manage the change process and the transition to a new company. They do so despite the reality that the change may be orders of magnitude beyond what they may have accomplished in the past.

This common response should not be surprising. After all, in most communities there is only one institution that can be considered an "expert" at the electric utility business, and that is the local utility. And that business is traditionally rather stable, with the time between major fundamental changes often measured in decades. After handling whatever comes along for decades, an over-confidence in one's ability to handle new challenges can be expected. Management responds with what it believes are substantial actions but which are, in fact, only fine-tuning. This error eventually becomes apparent, but not until damage in the form of added costs and delayed schedules are unavoidable.

While we discuss this tendency here somewhat in the abstract, our experience tells us it is a tangible and likely outcome for most utilities facing quantum shifts in their business. We cannot overestimate the magnitude of the challenge that we think Hydro is facing. Hydro appears to understand the significance of the issue and stated:

> *"The MF and LIL assets will represent a "step change" addition to NL's electric system, requiring extensive preparation from a technical and operations readiness standpoint to ensure overall system performance and reliability."*[196]

Only time will tell whether Hydro's appropriate observation here can or will be carried out as described. As we will discuss below, Hydro's approach so far seems closer in some cases to "fine-tuning" than the quantum or "step change" that we consider necessary.

C. Hydro's Management of the Transition

Liberty's analysis of Hydro's transition management scheme initially focused on the dedicated teams put in place to manage the major components of the transition. Recent changes at the executive level,[197] however, will have a major impact on transition management. We continue to believe that the work "on the ground" by the transition teams will be critical to success. We have in the past and in this report made clear our views about Hydro's operating culture, which in our opinion required serious improvement even before the pending transition to the "new company." That type of cultural transition is normally within the purview of executive management, not the transition teams, making the recent management changes of paramount importance. Specifically, Liberty believes that the success of the transition will be in the hands of the new executive leadership.

1. New Management and the Transition

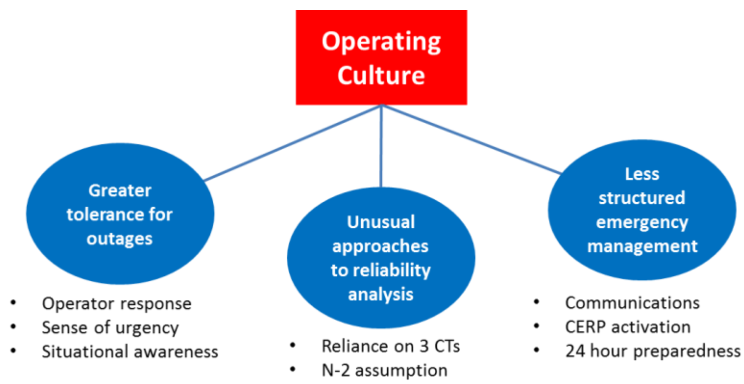
Hydro's operating culture has been a major issue in our judgment since we first started work related to the IIS more than two years ago. We have observed what in our experience was a somewhat unusual approach towards reliability. In our Interim Report, "we found that Hydro's practices vis-à-vis reliability standards did influence the supply conditions that contributed to the January 2014 interruptions, indirectly through a culture more tolerant of rotating outages and directly through the long-established reserve criteria and how the company has implemented them."

[196] Hydro slides from a meeting with Liberty on June 6, 2016
[197] A new Nalcor CEO and a new Nalcor Board were put in place in April 2016. A new President of Hydro was put in place in June 2016.

With respect to the March 4, 2015 outage when Hydro again experienced the need to shed load in a system disturbance, this time due to a voltage collapse, Liberty's analysis of the event, stated:

> *Counterbalancing these positive actions, Hydro has continued to plan for and react to contingencies less aggressively than do many other utilities. Liberty observed such an approach in our work associated with the January 2014 outages. Hydro's operating culture continues to comprise a matter of concern. With the operating culture issue identified in the aftermath of the January 2014 incidents, it nevertheless appears that Hydro has not accepted changing that culture as a priority. Liberty found that Hydro's reliability culture contributed to the causation and to the management of the March 4 event.*

Figure VI.1: Operating Culture



Liberty further explained its reasons for this conclusion, with details listed in the accompanying diagram from the report. Hydro's reply to Liberty's March 2015 Outage Report did not acknowledge the culture issue, and was generally non-responsive regarding Liberty's specific recommendation to "establish a more robust operational philosophy regarding reliability." The final paragraph of the Hydro response indicated that "Hydro will consider Liberty's advice and recommendations in future planning as it continues to build on the work completed in 2015 with respect to improved reliability for 2016 and beyond." Liberty therefore believed at the time, December 2015, that Hydro still did not accept that the long-standing culture issue is a valid concern.

Hydro's thinking on reliability, and specifically its approaches to analysis of reliability, was again prominent in the 2015 prudence review. Liberty was critical of Hydro's actions as applied to black start solutions and the Holyrood Unit 1 2013 turbine failure and the analysis of further lube oil failure exposures. The Liberty report on the March 4, 2015 outages also cited Hydro's need to "enhance the skills and capabilities it brings to reliability engineering and analysis."

In April 2016, Liberty met with Hydro's then-President to discuss the culture issue. He reported a number of initiatives had been implemented in Hydro's day-to-day operating practices to address this issue, including senior management involvement in daily operating discussions and the establishment of the prevention of customer outages as a high priority. A new President has been put in place since then and the status of these initiatives is unclear. We reiterate our past recommendations on the criticality of improving Hydro's approach to reliability analysis and operations. Future reliability depends on such people-related improvements as much as it does on the billions of dollars of new investment.

2. The Transition to Operations (TTO) Team

A Transition to Operations organization which is described in this section has been formed to manage the integration of the new assets into the Hydro organization and system. At the time of writing this report it is not known whether the April, 2016 executive changes will result in any changes, in the nature, structure, mission, or plans of the organization. We provide comments on what has been made known to us so far.

a. Structure

The key feature of the TTO is a full time, dedicated Vice President (VP) leading a four-team structure. That VP teams with the Project Director in a series of dotted line arrangements. In the new structure announced in April, 2016, the executive level is now split between generation and transmission, with an Executive VP in charge of each.

The four teams and their reporting relationship to the VP TTO are:

- Ready for Operations (RFO) – dotted line to VP TTO
- Building the Production Organization (BTPO) or operations readiness – reports to VP TTO
- Ready for Integration (RFI) – reports to VP TTO
- Ready for Commercial Integration (RFCI) – dotted line to VP TTO.

The VP TTO also chairs a high level Steering Committee comprised of about a dozen executives. The Steering Committee is charged with:

- Executive level oversight for the planning and execution activities of the transition to operations teams
- Approval of deliverables and work plans of the transition teams, and review of progress against the plan
- Guidance and direction on key strategic transition issues
- Resolution of issues escalated by the TTO teams
- Oversight of liaison and coordination with key internal and external stakeholders.

The Steering Committee also includes representatives from the Department of Natural Resources (DNR).

The organizational approach chosen is complex and in many ways cumbersome. Analyzing it is therefore not straightforward. Liberty found both strong and weak points associated with the approach.

i. <u>Strong Points</u>

A guiding principle stated by the TTO is the requirement for “a high level of cross-functional collaboration and information sharing.” This recognition of the need for involvement and direct participation in the transition by a wide variety of organizations is a strength. More importantly, this concept is reflected, at least so far, in the planning and structuring of the TTO effort. The Steering Committee is composed of high level managers from throughout the company. To the extent it is indeed able to get the active participation and real commitment of this level of management, the TTO will be empowered greatly, with good chances for success. This arrangement provides for both high-level participation and company-wide participation, a double benefit.

As we discussed future plans with Hydro personnel, we noted a common theme of personnel development. TTO management obviously places a high priority on assuring that Hydro people develop the skills needed for the future. Where this is not practical, the Company plans to retain contractors to perform the work. Further, vendors and contractors generally have contractual responsibilities to involve Hydro people and provide training as necessary. Liberty believes that management has a strong focus to provide what it believes will be a capable staff for future operations. While this is a strength, as discussed below, we do not believe that the implementation actions go far enough.

ii. Potential Weak Points

We noted earlier that the TTO organization is somewhat complex and cumbersome. Specifically, there are many dotted lines, to the extent that reporting relationships and accountabilities are not always clear. This is especially apparent in the reporting relationships of the key transition teams to the VP TTO. Of the four teams, two report directly to the VP TTO, while the other two report elsewhere. There is a dotted line relationship between the latter two and the TTO.

We noted above that the composition of the Steering Committee was a strength, but it can easily become a weakness if not managed properly. Achieving the dedication and commitment of so many high level people will not be easy. Executive management will have to set priorities, and the success of the Steering Committee, and perhaps of the TTO altogether, will be a function of executive management's commitment to ensuring that the required work is a priority.

Our review of the TTO effort, including the work of the teams, suggests that the work is still in a planning phase. In other words, the teams are deciding what needs to be done and developing plans and schedules for doing it. There is little evidence of a pending shift from planning to production, which might be expected given the short time the teams have been in place. But the available time cannot be wasted, and in our opinion a shift to a production mode must take place with a greater sense of urgency. It might be argued that the announced delays in Muskrat Falls will mean the transition work can be relaxed somewhat. TTO management has stated that any relaxation in its plans would be an error, and they remain committed to moving ahead at a fast pace regardless of any further delays in the project. We agree and note that a successful transition will be a challenge, even with the project schedule delays.

The primary reason for pushing ahead aggressively at this time, regardless of project completion dates, is the reality that the organization is yet to prove itself in a production mode. While management believes this organizational structure and approach will be effective, it might not be. It is therefore critical that the new organization be in place as soon as possible and begin producing in accordance with its plans.

TTO management seems to be placing a high priority on the development of detailed work plans and effective mechanisms for tracking against those plans. This is an appropriate and valuable attribute of the proposed management process. We observed, however, that the process does not yet appear to be in place. While TTO managers seem committed to the planning and tracking process, there was not a common understanding of what that process was or what it will be in the future. A strong project management system is an urgent priority.

We discussed earlier that management places a high priority on personnel development. While this is positive and the current plans are good, we are somewhat surprised that Hydro is not considering hiring staff from the outside with experience in the technologies associated with the new assets. Hydro states that they are indeed acquiring such skills, but in the form of temporary contractors. While we agree that temporary contractors are likely to be helpful, we also believe it is critical for Hydro to build the skills and capabilities to prudently manage its assets. Hydro's belief that it can take on major new technologies with the same people is an example of the kind of over-confidence about which we cautioned earlier. The HVdc system will be in place for a long time, and an indefinite reliance on contractors for most knowledge will not be appropriate. In addition, Hydro needs to strengthen its skills and capabilities in other technical areas as well, as we will discuss in more detail later.

We finally note that the TTO has many vacant positions. A heightened sense of urgency on the schedule should also produce a faster pace in getting the required resources on board.

3. Ready for Operations Team (RFO)

The primary mandate of RFO is the turnover of equipment to the asset owner, Hydro Operations. The team has a staff of 20-25 and reports to project managers. RFO plans to recruit and establish site teams for Soldiers Pond, Muskrat Falls, and Churchill Falls in 2016. In addition, the group plans to have the Project Completion System (PCS) implemented and contractor training completed in 2016.

RFO responsibilities include:

- Execution of project completions
- Monitor safety and environmental completions performance
- Support project quality and schedule
- Report on completion progress of the facilities
- Perform surveillance of contractor deliverables
- Execute asset turnovers to operations, including the provision of O&M documentation.

4. Building the Production Organization Team (BTPO)

The BTPO team has the broad responsibility to assure that everything necessary is in place to facilitate safe and reliable operation of the new assets. Specifically, the BTPO mandate is:

- Planning and oversight of all activities necessary to ensure Hydro's operational readiness to receive, operate and maintain Muskrat Falls assets; and
- Design of the operations and maintenance strategies and development of the plans, systems and procedures to ensure sustained safe and reliable operations.

Staffing of 15-20 people is expected for the BTPO, but only four people were in place as of April 2016, including experienced leadership. The organization appears well-conceived and properly located at the project offices in St. John's. Our concern at this point would be the need for a more aggressive transition to producing the promised deliverables, which requires an immediate emphasis on staffing all of the BTPO positions. We consider the small current staffing level to be a problem.

5. Ready for Integration Team (RFI)

The RFO team is primarily focused on the physical operating challenges, whereas RFI's responsibilities include engineering tasks. The overarching mandate of the group is to ensure reliable integration of all of the new assets, including the Maritime Link, into the IIS. To accomplish this, the team is charged with the following specific tasks:

- Ensure System Planning input prior to completion of the design and award of contracts
- System studies
- Oversight of the existing Interface Management System
- Review and comment on specifications, drawings and other documents
- Participate in the factory and site acceptance tests
- Provide personnel into all project phases in coordination with BTPO
- Develop startup and shutdown procedures
- Outage coordination
- Develop and advance reliability compliance (NERC/NPCC).

It is clear that RFI will play a pivotal role in the integration of the new system and the resulting level of reliability. The team has experienced leadership, and operates from the project offices in St. John's. The scope of work, the criticality of that work, the technical complexity of the work, and the need to coordinate with many other organizations and committees, both within and external to Hydro, raise the question as to how coordination will be accomplished effectively by six people. While the team is supplemented for studies by a consulting firm and much of its other work will be coordination, the small size of the organization raises real concerns.

6. Ready for Commercial Integration Team (RFCI)

The RFCI team reports to the General Manager of Commercial Management and Integration. The General Manager is affiliated with the VP-TTO through a dotted line relationship and reports directly elsewhere. The four main areas of the RFCI are:

- Commercial
- Legislative
- Control over hydro-electric resources
- Regulatory (including rates and open access).

It is clear that these are critical roles but they may not be, or need to be, as closely integrated as the rest of the TTO organization. We note that the Government of Newfoundland and Labrador has a critical path role in NERC compliance and the establishment of open access, but there does not appear to be a clear understanding of what is required and when. We have also discussed other important information that is lacking, including rate treatments and hence Hydro's future financial position and the treatment of interconnection transaction revenues and costs, all of which would be issues to be dealt with by this team.

As these are topics of paramount interest to stakeholders, we recommend that the plans for this work be given greater visibility and that results be made available to stakeholders as soon as reasonable.

D. Preparing for Reliable Operations

We have discussed above the steps Hydro is taking in the transition years in order to accept and manage the new assets. In addition, Liberty believes there are a number of initiatives that are either underway or should be instituted. These initiatives are aimed at developing the capabilities and processes to assure that the assets are operated effectively for their expected long life.

1. Organizational Capabilities

There is a critical need for new skills and capabilities to accommodate the new technology that Hydro is acquiring. These are primarily technical skills associated with the HVdc system. There are, however, other, more traditional skill requirements for which Hydro can and should improve its capabilities. The pending shift to a new system provides not only an urgent need, but also an excellent opportunity, to meet that objective.

We discussed some of these improvement needs earlier in the context of the new system. The new assets should improve the reliability of the IIS if properly operated; but our opinion, which we have made clear in prior reports, is that Hydro has more to do to acquire the skills and capabilities to manage the new assets in an optimum and reliable fashion.

Judgements on organizational adequacy will always be subjective, with black or white determinations unlikely. This is therefore not a question of what is acceptable or not, but a question of the degree to which improvement of the organization is possible and appropriate. Everyone can agree that any organization can always get better, but that is not a fair criterion. We point to specific opportunities, and explain why it is important for Hydro to seize those opportunities. Liberty sees the opportunities in four areas:

a. System Operations

Liberty has repeatedly stressed the need for a shift in Hydro's operational culture and philosophy, specifically with respect to how operations looks at reliability.

It is clear that there were problems in the past, and that the challenges of the future will be greater. Hydro operators will be presented with critical operating restrictions on the new HVdc system, and operators will be working in an interconnected system. We believe organizational improvements are appropriate now, and will become even more important in the years ahead.

b. Reliability Engineering and Analysis

Liberty has in its past reports been critical of the approaches Hydro has applied when analyzing operating contingencies and considering the potential for upsets. The meaning of N-2 contingencies and how they are interpreted,[198] the role of common mode failures in reliability

[198] We refer here to the N-2 question discussed in our analysis of the March 4, 2015 event. In that case, Hydro considered the failure to bring a unit back from an outage on time as one leg of an N-2 event.

analysis, analysis of black start options, evaluation of "rare" events and what preparations are appropriate, over-reliance on troubled assets, and over-confidence from lack of prior failures, are some of the examples that suggest an unusual approach on Hydro's part. While Hydro has a rationale for its analyses, we do not believe that the rationale is often consistent with what we generally see at other utilities. Liberty believes that improving the capabilities of the organization in the area of reliability analysis will lead to better decision-making and a more reliable system.

c. Planning

Liberty has worked closely with Hydro's planning organization, and found them to be responsive. We believe that Hydro has acted constructively in responding to the recommendations of Liberty and others, with the result that major improvements are now in place in its supply planning processes. However, we note some issues with the effectiveness of planning activities. The assessment of the supply situation over the last few years has demonstrated significant weaknesses, including the following:

- Hydro did not fully accept and act upon the need for a new CT until faced with the conclusion in April 2014 that there was a high risk of further power supply disruptions.
- Despite the prompt addition of a larger-than-planned CT and the securing of about 60 MW of interruptible load, Hydro almost immediately found itself with serious supply questions again.
- The supply issue became aggravated yet again when thermal units failed to perform as predicted.
- And Hydro apparently failed to recognize the value of the proposed new TL267 line as a mitigation of supply-related issues, which justified an earlier in-service date than originally planned.

In addition, in Liberty's March 2015 Outage Report, we cited a lack of communication regarding the vulnerability of the system on that morning. The outcome that day may have been different if system operators and Holyrood plant personnel were made aware of the vulnerability.

We appreciate that planning in times of uncertainty is neither easy nor fail-safe. We further recognize that the technical elements of planning are subject to other business priorities. Nevertheless, the need for crisp planning and analysis of the IIS both pre- and post- Muskrat Falls, must be a high priority. The addition of further strength to the organization in terms of personnel, systems and processes will significantly increase Hydro's ability to properly plan and strengthen confidence in Hydro's ability to properly plan the system.

d. Asset Management

From a supply perspective, Hydro's asset management program has a critical role as it is one of the three solutions to the near-term supply issues. The three are: (a) more generation, (b) less load and (c) higher availability of the generating units. Hydro responded as Liberty recommended in its Interim and 2014 Reports in all three areas, with: (a) a new CT, (b) more interruptible load, and (c) aggressive planning and execution of maintenance work and capital improvements.

Unfortunately, Hydro suffered major availability issues in the winter of 2015/16. There were failures at both Units 1 and 2 at Holyrood that led to the temporary unavailability of the units. In addition, an engine failure occurred on each of the Hardwoods and Stephenville CTs only six weeks apart. Finally, the Holyrood issues not only resulted in unavailability but, when the units were back in service, all three Holyrood units were de-rated to minimize the chances of further occurrences of the problem. The subsequent analysis by Amec Foster Wheeler has allowed Units 1 and 2 to return to full rating while Unit 3 will continue to be de-rated by 10% temporarily.

Hydro depends on older thermal resources for adequate power supply, including the Holyrood units and two CTs at Hardwoods and Stephenville. The two CTs have a very weak performance record. The potential inadequacies of these machines have been known for a long time, so much so that Hydro has devoted extraordinary measures to assure their reliability. Repeated adequacy assessments, aggressive maintenance, extensive capital improvements, and broad availability of spares have been tactics aimed at extending the life of these thermal units to post-Muskrat Falls as well as assuring they operate reliably for their remaining years.

The details of these recent failings and their impact on near-term power supply are discussed in Chapter II of this report. The point here is that the asset management program seems to have failed in maintaining these critical assets in a reliable condition despite additional measures by Hydro. The continued availability and reliability of these thermal units is questionable well into the future. This is a tragic outcome that is more aggravated with the delay in the in-service date for Muskrat Falls.

Under ordinary circumstances, the failures of old machines might be expected as they are not worth a lot of new investment and one must work hard and hope for the best to hold them together. But this is not the case here. Quite the contrary, the analysis of the equipment has been done and the specific actions to extend their lives and assure reliability have been made over a period of many years. Yet the Holyrood units demonstrated themselves to be extremely vulnerable and the CTs are likely to continue the pattern of something significant seeming always to go wrong.

The conclusion that changes are necessary in Hydro's approach to power plant asset management is unescapable. The failures in the management of the thermal units are extreme and are likely to have adverse consequences for a long time.

e. Summary

The problems discussed above lead to the inevitable conclusion that Hydro has a challenge in ensuring that the right skills and technical expertise are in place It is urgent to do so before the new system is in place. On the positive side, the timing is good. The new system changes Hydro's needs and provides a good opportunity to rebuild and strengthen the organization for the future. We believe Hydro can succeed in this regard by undertaking the following actions:

- Conduct a thorough review of the skills and capabilities needed for the future, including both traditional skills in operations, planning, reliability engineering and asset management, as well as in the unique new requirements for the new system.
- Develop high standards for managerial and technical positions.
- Define gaps with required skills and capabilities.

- Develop the required skills and capabilities through a combination of internal development and, where appropriate, new hires.

While the above discussion focused on the weaknesses we believe exist at Hydro with respect to technical skills, we also acknowledge that Hydro is taking many positive steps to build the skills it needs for the future. Some of the actions Hydro is taking to develop people and the required skills, which we believe are positive, include the following:

- The transition of Holyrood people to Muskrat Falls has been and continues to be a major challenge. Hydro took steps several years ago to assure it could retain a viable workforce at Holyrood for its remaining years. The reality that Holyrood cannot close the day that Muskrat Falls starts up creates a phasing problem and Hydro is planning that now. While this issue, including the desire to retain and protect people, is difficult it appears to have been well-managed so far.
- Hydro has embedded engineering personnel in the project organization from the start. These people will evolve into the RFO organization and finally into long-term Hydro engineering positions. This is a very strong hands-on personnel development opportunity.
- Hydro people will also take part directly, as a training opportunity, in system dynamic and stability studies, control and protection system factory acceptance tests and commissioning. Contractors each have contractual requirements concerning the training of Hydro people.
- Hydro has made the decision to use contractors for certain operating and maintenance activities in the early years. It is anticipated that this will also be a training opportunity for Hydro personnel who could take such responsibilities in the future.

2. Asset Management

Hydro is planning and implementing its asset management program to take on the responsibility for the new assets. We have noted past problems in the program and have suggested above that organizational improvement would be appropriate. Here we discuss the specific plans Hydro is pursuing to prepare its asset management process.

The BTPO team is accountable to put the required asset management program in place to support the new assets. The specific deliverables targeted by the group include:

- Systems in place to assure reliable, cost-effective operation and maintenance of all new assets
- Asset hierarchies developed
- Asset criticality completed
- Critical spares analysis completed and spares stocked
- Maintenance tactics developed
- Standard operating procedures developed.

The strategy for spare parts is particularly interesting given the special challenges of the HVdc system being spread over a large geographical area and spares having to be located conveniently enough to facilitate rapid restoration. Hydro is taking the following actions:

- All contracts include recommendations on spares and provision of defined spares
- Spare power transformers will be provided

- The concept of "critical spares" with associated treatment is being applied
- Optimal storage locations are being developed to facilitate restoration.

The most critical aspect of asset management is likely to be the maintenance strategies and processes developed by the BTPO team. With these deliverables at least a year or two away, the effectiveness of those programs cannot be evaluated. The degree to which the organizational recommendations presented earlier for asset management are implemented will play a large role in assuring success.

3. Emergency Preparedness

Progress in emergency planning has been limited, with detailed emergency response and restoration plans not available until much closer to operation. We believe that there are reasons for a greater sense of urgency. The new technology associated with the HVdc system and the converter stations suggests the need for a learning period. In addition, outages of the OHL may be especially problematic in light of the potential for bipole outages and the difficult environment in which restoration activities must be carried out. Finally, the area of emergency response is one in which Hydro has demonstrated some weakness in the past. A more aggressive approach now would therefore seem appropriate.

Other than the timing, there is little to comment upon in emergency planning at this time. The BTOP has demonstrated a sensitivity to key issues in meeting this challenge. It has identified a number of critical deliverables, including:

- Identification of operational risks
- Preparation of mitigation plans
- Restoration-related training for operators, maintenance and repair personnel
- A focus on and priority for emergency preparedness and service restoration
- Preparation and communication of emergency response manuals
- Engagement of external support agencies.

OHL restoration is a particular concern due to the possibility for an extended bipole outage. For planning purposes, Hydro has stated that any outage of the OHL will be restored within two weeks, with the presumption that plans will be put in place to assure that this is the worst case. Those plans will include:

- Purchase of all materials needed for line restoration and storage of those materials at strategically located sites
- Availability of all-terrain equipment to assure access to remote sites
- Development of an access and restoration trail-way system as part of the initial construction
- Design of temporary emergency structures that can be flown to remote sites
- Mutual aid agreements with other utilities.

These are all positives and indicate that at least Hydro is thinking of these important considerations and beginning to conceptualize plans. On the other hand, recognizing the magnitude of the challenge of repairing significant OHL damage in extreme weather and in harsh terrain, it is hard to have confidence that two-weeks is the upper limit for an OHL-related bipole outage. The consequences of prolonged outages will be significant, especially in the winter and during periods of peak load.

In view of the critical importance of effective emergency management and restoration plans to IIS reliability, the Board should require, at least six months before the LIL is energized, the preparation and submittal by Hydro of emergency response plans for events leading to IIS outages, including multiple OHL tower failures in remote areas.

4. Service Support

In our discussion above of Hydro skill needs, we discussed Hydro's intended reliance on contractors. Although we have recommended obtaining qualified internal staff, we also recognize the wisdom and necessity of utilizing contractors during the transition and in the early years of operation. In this regard, Hydro is taking appropriate action. Contractors and equipment vendors will be responsible for commissioning, technical support, services, and training and involvement of Hydro personnel. In addition, during the early years, service contracts will be in place to provide various operating and maintenance functions, including:

- Converter station O&M
- Facilities maintenance
- Specialized maintenance support
- Emergency response and restoration services for the undersea cables
- GIS technical support.

The strategy for the use of contractors is appropriate at this time; however, the missing piece is how Hydro intends to transition from a high reliance on those contractors to a more reasonable long-term balance. Accordingly, Hydro should be developing plans at this time for how it plans to acquire and train internal people to support the eventual transition away from contractors, where appropriate.

5. Risk Management

Hydro plans to apply its existing risk management skills and capabilities to the transition process as well. A transition to operations risk register is being maintained and Hydro is tracking, for each identified risk:

- Potential impacts
- Mitigation actions developed or planned for the future
- A responsible manager
- Tracking of status.

The TTO Steering Committee has a priority on risk management and plans full implementation of risk management processes by the third quarter of 2016.

6. NERC Compliance

With its connection to the North American grid via Nova Scotia, Hydro faces potential new standards for its system and its interfaces with others. In addition, Hydro's desire to engage in market transactions with others in North America brings the requirement of granting others access to the IIS. These needs have been known for some time, and Hydro has been taking steps to address them.

A key deliverable of Hydro's RFI team is the preparation "of a multi-year reliability compliance program in accordance with the Provincial Reliability Framework". To our knowledge, there is no Provincial Reliability Framework at this time. We are assured by Hydro that work is progressing in this area and it is working with the Government of Newfoundland and Labrador, which has the lead role, in this regard. However, we have seen no evidence on the status, plans, or deliverables. Discussions with Hydro have shed little light on what is happening and what has to happen to support interconnection with Nova Scotia. The Maritime Link is presently on schedule for energization in late 2017, so the reliability framework, NERC / NPCC compliance, and the legislation required for it should be a priority.

An external review and gap analysis on NERC compliance has been completed. The outcome of this will be integrated into the transition plan. Hydro has also retained a former VP of NERC as a consultant to assist in this process, which is an excellent initiative. Hydro notes, however, that "Government direction is required to finalize the implementation plan and cost".

7. Reserve Sharing and NSPI Transactions

a. Background

A major benefit of interconnection with another electrical system is the sharing of reserves. From a probabilistic perspective, a lower percentage of reserves can be appropriate when the risk is spread over more than one system.

At the present time, the reserve requirement on the IIS is the loss of the largest unit plus 70 MW, which equated to 240 MW before the de-rate of the Holyrood units. In the future system, under NPCC requirements, the IIS reserve will be essentially the same, although the way it is determined is different. NERC requires that ten-minute reserves be available for the loss of the largest unit plus thirty minute reserves for one-half the second contingency loss. This amounts to 229 MW in the future system.[199]

b. The Contemplated Reserve Sharing Group

NPCC provides for reserve sharing groups.[200] Such groups are made up of balancing areas who execute a reserve sharing agreement. The contemplated members of the potential reserve sharing group envisioned by Hydro include Nova Scotia Power (NSPI) and New Brunswick Power (NPB). The NBP balancing area also encompasses Prince Edward Island and parts of northern Maine.

In early 2015, the three companies, cooperating as members of the Maine and Atlantic Technical Planning Committee (MATPC), agreed to a joint study effort. The role of MATPC is to review intra-area transmission and generation plans with regards to transmission reliability and impacts

[199] "Ready for Integration Overview", slide presentation from April 19, 2016, Slides 31-32.
[200] NPCC Directory #6

on the MATPC interconnected system.[201] The scope of the study and the status of the work is as follows.[202]

- Review existing Open Access Transmission Tariffs (OATTs) and reliability standards with respect to the potential for reserve sharing.
    - The parties have concluded that the NSPI and NBP OATTTs permit the concept of reserve sharing among them and the IIS.
    - The parties have also reviewed as ground rules NERC BAL (balancing) and EOP (emergencies) standards
    - NERC Directories #5 (reserves) and #6 (reserve sharing groups) are applicable
- Prepare joint bases cases for power system analysis.
    - All three parties have completed common interconnected system cases
    - Adjustments to the NSPI model may be required to reflect their new capital plan
- Each utility to determine transfer limits and available reserves
    - NBP-NE maximum single contingency load loss for all transfer scenarios = 375 MW
    - Firm NB-NS transmission capacity of 200 MW – existing firm reservation = 125 MW
    - NSPI to determine transfers to the IIS based on 375 MW available at Cape Breton.
    - Hydro can provide about 300 MW at Bottom Brook.
- Prepare report on technical feasibility
    - Awaiting technical results
- Engage generation planners to determine economic feasibility

Hydro reports that it expects the required studies to be complete by September 2016.

c. *Maritime Link Transfers*

It is clear that the Maritime Link is a critical element in the future reliability of the IIS. Conceived as an export vehicle to allow Nova Scotia access to Muskrat Falls power, the Link has evolved to far more important purposes from Hydro's perspective. Most importantly, the Maritime Link is interruptible to the extent supply on the LIL is lost. The Maritime Link load therefore, in a limited way, looks like spinning reserve to the IIS.[203] In addition, the flow on the Maritime Link can be reversed with the result that several hundred MW in supply from Nova Scotia can be made available to the IIS.[204] As discussed at length throughout this report, this latter feature has been called upon on numerous occasions in Hydro's reliability analyses and power supply adequacy assessments. There is no question that the potential benefits of the Maritime Link are significant for the reliability of the IIS.

The full realization of such Maritime Link benefits, however, requires that a reliable supply of power is indeed present at the other end of the link. The parties have regularly referred to 300

[201] PUB-NLH-502

[202] "Ready for Integration Overview" presentation by Hydro transition management, April 19, 2016

[203] The ML load is effectively spinning reserve but only related to the loss of the LIL. It is not literally spinning reserve in the sense that it is of no reserve value for the loss of on-island generation.

[204] Note that this "reversal" is not instantaneous. In practice, the ML would be tripped. The NS supply could then be lined up and the ML re-started in the other direction, perhaps an hour later.

MW or more available to be wheeled from Nova Scotia to the IIS over the Link. To depend on this capacity, one must first assume that Nova Scotia is maintaining reserves sufficient to (1) immediately cover the loss of its imports on the Maritime Link and (2) provide an additional 300 MW to ship to the IIS a short time later. Discussions between the parties are underway to secure such arrangements, but they are not yet in place and, given the large commitment involved, may or may not come about as Hydro desires. In PUB-NLH-280, Hydro reports:

> *"Preliminary discussions with both NSPI and NBP have indicated a willingness to negotiate arrangements that in the event of an emergency in Newfoundland, standby generation in the Maritimes could be started to provide up to 300 MW of capacity."*

Also on the positive side, Nova Scotia has been aggressive in lining up renewable capacity in recent years with the result that its coal fleet regularly operates at relatively low capacity factors. In fact, one coal unit on Cape Breton is slated for retirement in 2019. One must assume, however, that any use of such "excess" capacity for the benefit of the IIS will come at a price, if at all.[205]

We are left with the reality that the critical reliability benefits of the Maritime Link for the IIS are not yet in place, but should be a high priority.

8. LIL Operating Constraints

A common theme in the reliability discussions in this report is the need to operate the LIL prudently to optimize reliability and minimize risk. Hydro is aware of such considerations and has indicated that such operating limits will be established as prudent. For example, on a peak day, Hydro indicates that the LIL will carry 120 MW of spinning reserve.[206] The operating limit of the 900 MW capacity LIL for the benefit of the IIS is therefore about 573 MW (900 MW, less Nova Scotia load, less losses, less 120 MW reserve).

Other operating constraints may prove to be appropriate. It should be obvious that the less load on the LIL, the less the consequences of a bipole trip. In most circumstances, a permanent bipole outage will lead to UFLS, but this might not be the case at low loads.

We believe that the operating culture issue, discussed elsewhere in this report, is tied to Hydro's willingness to establish and abide by prudent operating limits on the LIL. We again stress the importance and priority of that objective.

E. Effectiveness of the Transition Process

We have discussed each of the elements of the transition process above, commenting where Hydro's plans appear adequate and where they need improvement. We must emphasize, however, that the discussion is largely limited to "plans," and not accomplishments. Hydro has identified what needs to be done, but there is no evidence as yet that it will be as effective in actually implementing those plans. The complexity of the transition organization, the numerous

[205] Any plan involving added coal generation for the benefit of others, given NS's large investment in clean energy, is likely to be problematic. Note that NS's investment in clean energy includes its share of MF generation.
[206] "Ready for Integration Overview", slide presentation from April 19, 2016, Slide 26.

vacancies, the limited plans for new talent, concerns with existing organizational capabilities, current organizational upheaval, and delays in Muskrat Falls and the LIL are all reasons to suspect that the implementation challenge will be very difficult. Hydro needs to establish a greater sense of urgency and demonstrate that it is up to this challenge.

We also noted that Hydro's emphasis on detailed transition plans as well as the use of a professional planner are positives, however, there was considerable misunderstanding on just how these plans would be used and tracked, and the level of visibility they would provide. It is urgent that this system be implemented as soon as possible and that it give a high degree of visibility to what needs to be done and when, and that it provide continuing status and analysis of the transition process. Hydro must be able to demonstrate that its plans are clear and it has the ability to execute those plans. IIS reliability is closely correlated to the degree of success achieved in the transition. Accordingly, the Board should require detailed plans from Hydro and periodic reports, perhaps quarterly, on progress against those plans.

F. Conclusions

VI-1. The challenges facing Hydro (large new generator, new HVdc technology, and interconnection with North American systems) are so far reaching and significant that they will substantially alter the identity of Hydro and influence most of its organizations.

VI-2. Based on our experiences with other utilities facing substantive change, there is a real danger that Hydro will underestimate the degree of the transition challenge and will limit its efforts to fine-tuning of the organization as opposed to the quantum changes necessary.

VI-3. The detailed plans now being prepared by Hydro's transition teams will be the critical management tool in assuring a timely and effective transition process.

VI-4. The work of the transition teams seems limited primarily to planning initiatives at this time and may be slowed by inadequate staffing.

VI-5. Hydro's plans for individual personal development through the transition are strong, but the reluctance to hire new talent externally is not appropriate for the needs of the new system.

VI-6. Hydro's high reliance on contractors in preparing for operations and in the early years of operations makes sense; however, the lack of a plan to acquire and train people to support the eventual transition away from contractors, where appropriate, is worrying.

VI-7. The transition to the new electric system provides both the need and the opportunity to significantly enhance organizational skills and capabilities, including in new technical areas (HVdc) and traditional areas in which there have been issues, including system operations, planning, reliability engineering and asset management.

VI-8. It is not yet clear that management will sustain recent initiatives in response to Liberty's conclusions on the need for an enhanced reliability culture and philosophy of operations.

VI-9. The TTO Steering Committee has the potential to be the key to the success of the transition effort, provided that the requisite management commitment can be sustained.

VI-10. The membership of the TTO Steering Committee, including the Department of Natural Resources, is an asset.

VI-11. The efforts of the RFCI team do not appear to be integrated into the full TTO efforts to the same degree as the other teams.

VI-12. Given that the Maritime Link will be in service in about one year, there does not appear to be suitable progress in resolving issues relating to market transactions, such as responsibility, rate treatment, open access, and avoidance of conflicts between marketing and operations.

VI-13. Emergency restoration plans, including those associated with the OHL, have not yet been developed but will be critical to containing potentially catastrophic outages of the bipole.

VI-14. Hydro has been taking steps towards NERC/NPCC compliance, but a specific plan for the activities to achieve this goal appears to be lacking.

VI-15. Government action and direction is required to complete the Provincial reliability framework, a prerequisite for NERC compliance initiatives as well as open access requirements, but there has been little visibility on the plans to accomplish this or the status of the effort.

VI-16. The full reliability benefits of the Maritime Link, and validation of Hydro's reliability analyses, require formal agreements with Nova Scotia Power and New Brunswick Power to assure that the proposed 300 MW backup supply for the IIS benefit will indeed be available in an emergency.

VI-17. The LIL operating constraints defined by Hydro will have a significant role in maintaining reliability of the IIS.

G. Recommendations

Recommendation VI-1. The transitions team's integrated schedule should be given high visibility, including provision of the detailed plans to the Board as well as periodic reports on status.

Recommendation VI-2. Hydro should increase the sense of urgency associated with the transition effort using tangible measures such as increased management expectations regarding progress and increased staffing.

Recommendation VI-3. Hydro should re-evaluate the adequacy of staffing in the RFI team.

Recommendation VI-4. Hydro should accelerate the filling of positions in the BTPO team.

Recommendation VI-5. Hydro should reconsider its plans to avoid new hires.

Recommendation VI-6. Hydro should develop a plan for the phasing out of contractors, to be replaced by internal resources, when appropriate.

Recommendation VI-7. Hydro should (a) define the new skills and capabilities required by the organization; (b) define the improvements needed in skills and capabilities in operations, planning, reliability engineering and asset management; (c) develop new, high standards for technical and managerial positions in those areas; (d) define gaps between future needs and current skills and capabilities; and (e) acquire the required skills and capabilities through a combination of internal development and external hiring.

Recommendation VI-8. Hydro should provide the Board with its plan for dealing with the cultural issue referred to in Conclusion VI-8.

Recommendation VI-9. RFCI activities in support of the transition should be given greater visibility including inclusion in the detailed transition plan.

Recommendation VI-10. A complete plan for how interconnection transactions will be managed, including definition of roles and responsibilities, rate treatment, and how all regulatory requirements will be satisfied, should be developed.

Recommendation VI-11. Hydro should prepare and provide to the Board at least six months prior to energization of the LIL, emergency response plans for events leading to IIS outages, including multiple OHL tower failures in remote areas.

Recommendation VI-12. A recommended plan for the completion of all activities, both internal and external, required to support NERC compliance and open access should be provided.

Recommendation VI-13. As the Board is likely to have some role in the management of the Provincial reliability framework, it should be party to current discussions on the formulation of that framework.

Recommendation VI-14. Hydro should promptly secure agreements with Nova Scotia Power and New Brunswick Power or, in the inability to do so, provide for other methods of addressing relevant contingencies.

VII. Summary of Conclusions and Recommendations

Chapter Two: Power Supply Adequacy and Reliability Pre-Muskrat Falls

Conclusions

II-1. The IIS remains vulnerable to supply-related disruptions until Muskrat Falls and the LIL begin reliable operation.

II-2. The Holyrood oil-fired units and the Hardwoods and Stephenville CTs, which have performed poorly, are primarily responsible for the system's vulnerability.

II-3. Hydro's recent assessment of supply adequacy indicates reliability violations which Hydro proposes to mitigate but not eliminate.

II-4. Liberty believes that supply risks are greater than suggested by Hydro's assessment.

II-5. Liberty believes that a more detailed pre-Muskrat Falls supply assessment, including adequate consideration of the risks, is likely to conclude that new supply is required in the near future.

Recommendations

Recommendation II-1. Hydro should conduct a new supply review that considers all risks, including the thermal assets and the planned reductions in the load forecast, and provide a risk-based recommendation on the need, timing and amount, if any, for new pre-Muskrat Falls supply.

Chapter Three: The LIL and the Maritime Link

Conclusions

III-1. The design of the LIL bipolar system includes the measures expected of a well-designed critical infrastructure project.

III-2. One weakness of the LIL bipole design is the lower rating of the electrode line conductors, as compared with the HV conductors.

III-3. The poles have been designed with overload capability, which minimizes the impact of the reduction in power delivery at Soldiers Pond in the event of a failure of one pole or a major element within a pole.

III-4. It may be necessary to operate the dc scheme with reduced dc voltage during bad weather conditions, damage to insulators, or forest fires.

III-5. The provision of proposed synchronous condensers appears to be adequate, provided that the models used are realistic and the recovery of the power transmission can be achieved in the time assumed by the simulation models.

III-6. Hydro has not yet studied re-strikes on the HVdc OHL, which would effectively double or possibly treble the duration for which power flow on one or both poles of the LIL stops.

III-7. Examination of events on the IIS will provide valuable information, and a potential insight into the future performance of the IIS, as the load and power flow increases.

III-8. The benefits of the ability to curtail the Maritime Link in the event of problems with the LIL or in the ac network have been shown by studies to be considerable, in terms of the requirements for inertia and spinning reserve.

Recommendations

Recommendation III-1. Hydro should consider the possible need for operation at reduced dc voltage in its planning of IIS standby power generation.

Recommendation III-2. Frequency excursions resulting from all major disturbances in the IIS and in the LIL should be recorded and analyzed, with the event being compared with a study to be performed by Hydro using detailed models of the LIL and the exact network configuration and LIL parameters (power and control settings), to identify discrepancies in the actual performance compared with the modeled system.

Recommendation III-3. Studies of the performance of the IIS should be performed not only with the Maritime Link in service, but also with it out of service.

Chapter Four: Reliability of Muskrat Falls

Conclusions

IV-1. The electrode line forms an important part of the overall HVdc circuit, and close attention is required for achieving high availability of this circuit.

IV-2. The electrode line design will cause flashovers, from the conductors to ground or to the tower, to transfer to the arcing horns such that the arc will self-extinguish as quickly as possible, which will reduce the number of outages caused by temporary faults, such as lightning strikes to the HVdc transmission line.

IV-3. When the Maritime Link is exporting power from the IIS to Nova Scotia, the ability to curtail the Maritime Link provides significant benefits to the IIS.

IV-4. It would be beneficial to the IIS if the Maritime Link were operated with back-up frequency control for the IIS system, both when the LIL is in-service and not in service.

IV-5. Multiple restrikes are likely, but none of the studies provided by Hydro included cases where more than one re-start attempt proves necessary.

IV-6. AC faults at Bay d'Espoir lead to UFLS, but Hydro has generally dismissed them as "exceptional".

IV-7. Numerous studies remain to be completed; their expeditious completion is essential.

IV-8. The LIL and the associated high inertia synchronous condensers have been designed to allow LIL operation to minimize the need for UFLS in the event of monopolar outages and temporary interruptions.

IV-9. Pole outages are estimated by Hydro to occur on average 9.36 times per year.

IV-10. There will likely be significantly more pole outages than predicted by Hydro.

IV-11. The Maritime Link is critical to the reliability of the IIS power supply

IV-12. In the event of bipolar outages, UFLS may take place.

IV-13. Hydro considers acceptable the occurrence of UFLS as a consequence of a bipole outage.

IV-14. The ability of the yet-to-be defined UFLS scheme to prevent system collapse after a bipole trip is of critical importance and hence makes the development of a successful scheme a high priority.

IV-15. Hydro estimates the average number of bipole outages to be 0.10 for the converter stations and 0.22 for the HVdc OHL, giving a total of 0.32, i.e., a bipole failure about every three years.

IV-16. Hydro considers under-frequency load shedding acceptable when a second fault happens while the LIL or the ac network is already in an N-1 condition (*i.e.*, an earlier fault has not yet been rectified).

IV-17. It is likely that Hydro has underestimated the potential number of bipole outages.

Recommendations

Recommendation IV-1. Hydro must clearly ensure the use of the best design and construction practices for the electrode lines, because they have significant potential for causing bipole outages.

Recommendation IV-2. Hydro and its converter station contractor should perform transient stability studies with multiple restart attempts for HVdc OHL faults.

Recommendation IV-3. Re-strike performance should be continuously monitored and recorded.

Recommendation IV-4. Hydro should undertake an investigation of ac faults at Bay d'Espoir, to determine what steps could be taken to minimize the impact of such faults.

Recommendation IV-5. Hydro should make space provisions for the installation of a 4th high inertia synchronous condenser near Soldiers Pond.

Recommendation IV-6. Hydro should include the complete plan for remaining studies on the Transition Team's integrated schedule, and monitor completion performance.

Recommendation IV-7. Hydro should take into account in its planning of the standby and reserve power capability of the IIS, the potential occurrence of the fault types mentioned in Conclusion IV-17.

Recommendation IV-8. The performance of the LIL should be rigorously monitored and recorded, using procedures such as those provided in Cigre Technical Brochure 590.

Recommendation IV-9. While loss of load on a bipole trip will be necessary, Hydro should study options, such as operating limits, to reduce incidents of UFLS.

Recommendation IV-10. While UFLS will be necessary in the event of most bipole trips, their impact on customers should be reduced by Hydro ensuring that sufficient generating resources and/or guaranteed power via the Maritime Link are available to be brought on line to meet the power demand of the IIS during a bipolar outage of LIL.

Recommendation IV-11. The critical role of UFLS in preventing system collapse on a bipole trip requires that development and implementation of the UFLS scheme receive a high priority as well as suitable oversight by the Board.

Chapter Five: Power Supply Adequacy and Reliability Post-Muskrat Falls

Conclusions

V-1. Major supply disruptions in the future should be significantly reduced by the combination of: (a) enhanced organizational capabilities as recommended in Chapter VI and (b) the resilience of the new Muskrat Falls system.

V-2. UFLS is a last resort to prevent total system collapse and hence, from planning and design perspectives, the number of instances should be limited.

V-3. The planned deign makes UFLS inevitable on the loss of the bipole, (except perhaps under light load conditions); UFLS can be expected once or more every three years.

V-4. The extent to which Hydro can count on the Maritime Link as a source of dependable backup supply and the competitiveness of such supply versus new IIS generation are far from clear.

V-5. The need for added supply to mitigate loss of load on an extended bipole trip has not been sufficiently considered.

V-6. Numerous factors, both pre and post Muskrat Falls, are emerging, all of which point to the need for new supply, and the collective impact of these factors is the likelihood that new supply is needed sooner rather than later.

Recommendations

Recommendation V-1. Hydro should expedite efforts to determine (a) the availability of dependable reserves from Nova Scotia or elsewhere and (b) the competitiveness of those reserves versus new IIS generation.

Recommendation V-2. Hydro should evaluate the degree to which new capacity, via dependable Maritime Link supply and/or new CTs, is required to assure that customer outages due to loss of the bipole are limited to those caused by UFLS and those circuits are promptly (hours) restored.

Recommendation V-3. Hydro should prepare a new resource plan that, as necessary, includes new CTs and the dependable portion of any Maritime Link imports, and addresses all of the supply-related risks currently confronting Hydro.

Chapter Six: Transition to Operations

Conclusions

VI-1. The challenges facing Hydro (large new generator, new HVdc technology, and interconnection with North American systems) are so far reaching and significant that they will substantially alter the identity of Hydro and influence most of its organizations.

VI-2. Based on our experiences with other utilities facing substantive change, there is a real danger that Hydro will underestimate the degree of the transition challenge and will limit its efforts to fine-tuning of the organization as opposed to the quantum changes necessary.

VI-3. The detailed plans now being prepared by Hydro's transition teams will be the critical management tool in assuring a timely and effective transition process.

VI-4. The work of the transition teams seems limited primarily to planning initiatives at this time and may be slowed by inadequate staffing.

VI-5. Hydro's plans for individual personal development through the transition are strong, but the reluctance to hire new talent externally is not appropriate for the needs of the new system.

VI-6. Hydro's high reliance on contractors in preparing for operations and in the early years of operations makes sense; however, the lack of a plan to acquire and train people to support the eventual transition away from contractors, where appropriate, is worrying.

VI-7. The transition to the new electric system provides both the need and the opportunity to significantly enhance organizational skills and capabilities, including in new technical areas (HVdc) and traditional areas in which there have been issues, including system operations, planning, reliability engineering and asset management.

VI-8. It is not yet clear that management will sustain recent initiatives in response to Liberty's conclusions on the need for an enhanced reliability culture and philosophy of operations.

VI-9. The TTO Steering Committee has the potential to be the key to the success of the transition effort, provided that the requisite management commitment can be sustained.

VI-10. The membership of the TTO Steering Committee, including the Department of Natural Resources, is an asset.

VI-11. The efforts of the RFCI team do not appear to be integrated into the full TTO efforts to the same degree as the other teams.

VI-12. Given that the Maritime Link will be in service in about one year, there does not appear to be suitable progress in resolving issues relating to market transactions, such as responsibility, rate treatment, open access, and avoidance of conflicts between marketing and operations.

VI-13. Emergency restoration plans, including those associated with the OHL, have not yet been developed but will be critical to containing potentially catastrophic outages of the bipole.

VI-14. Hydro has been taking steps towards NERC/NPCC compliance, but a specific plan for the activities to achieve this goal appears to be lacking.

VI-15. Government action and direction is required to complete the Provincial reliability framework, a prerequisite for NERC compliance initiatives as well as open access requirements, but there has been little visibility on the plans to accomplish this or the status of the effort.

VI-16. The full reliability benefits of the Maritime Link, and validation of Hydro's reliability analyses, require formal agreements with Nova Scotia Power and New Brunswick Power to assure that the proposed 300 MW backup supply for the IIS benefit will indeed be available in an emergency.

VI-17. The LIL operating constraints defined by Hydro will have a significant role in maintaining reliability of the IIS.

Recommendations

Recommendation VI-1. The transitions team's integrated schedule should be given high visibility, including provision of the detailed plans to the Board as well as periodic reports on status.

Recommendation VI-2. Hydro should increase the sense of urgency associated with the transition effort using tangible measures such as increased management expectations regarding progress and increased staffing.

Recommendation VI-3. Hydro should re-evaluate the adequacy of staffing in the RFI team.

Recommendation VI-4. Hydro should accelerate the filling of positions in the BTPO team.

Recommendation VI-5. Hydro should reconsider its plans to avoid new hires.

Recommendation VI-6. Hydro should develop a plan for the phasing out of contractors, to be replaced by internal resources, when appropriate.

Recommendation VI-7. Hydro should (a) define the new skills and capabilities required by the organization; (b) define the improvements needed in skills and capabilities in operations, planning, reliability engineering and asset management; (c) develop new, high standards for technical and managerial positions in those areas; (d) define gaps between future needs and current skills and capabilities; and (e) acquire the required skills and capabilities through a combination of internal development and external hiring.

Recommendation VI-8. Hydro should provide the Board with its plan for dealing with the cultural issue referred to in Conclusion VI-8.

Recommendation VI-9. RFCI activities in support of the transition should be given greater visibility including inclusion in the detailed transition plan.

Recommendation VI-10. A complete plan for how interconnection transactions will be managed, including definition of roles and responsibilities, rate treatment, and how all regulatory requirements will be satisfied, should be developed.

Recommendation VI-11. Hydro should prepare and provide to the Board at least six months prior to energization of the LIL, emergency response plans for events leading to IIS outages, including multiple OHL tower failures in remote areas.

Recommendation VI-12. A recommended plan for the completion of all activities, both internal and external, required to support NERC compliance and open access should be provided.

Recommendation VI-13. As the Board is likely to have some role in the management of the Provincial reliability framework, it should be party to current discussions on the formulation of that framework.

Recommendation VI-14. Hydro should promptly secure agreements with Nova Scotia Power and New Brunswick Power or, in the inability to do so, provide for other methods of addressing relevant contingencies.

Appendix A: The Liberty Consulting Group Project Team Resumes

John Antonuk

Areas of Specialization

Executive management; management audits and assessments; service quality and reliability management and measurement, utility planning and operations; litigation strategy; management of legal departments; human resources; risk management; regulatory relations; affiliate transactions and relations; subsidiary operations; and testimony development and witness preparation.

Relevant Experience

Electricity

Engagement Director for Liberty's operational audit of utility staffing levels of each New York electric and gas utility for the New York Public Service Commission.

Project Manager and witness on audits of fuel (primarily coal and natural gas) procurement and management practices of Nova Scotia Power, a review of the merits and mechanics of a company-proposed automatic recovery method for energy costs, and an audit of affiliate relationships (including coal, electric power, and natural gas procurement activities) performed for the Nova Scotia Utility and Review Board. Liberty has assisted the Nova Scotia Utility and Review Board in other reviews of Nova Scotia Power regarding storm outage and response, in rate cases, and in various other proceedings.

Engagement Director for Liberty's review the prudence of management decisions and actions of Newfoundland and Labrador Hydro concerning Island outages experienced during the winters of 2013 and 2014. This project sought to determine the costs related to these decisions and actions.

Project Manager for Liberty's prudence review of Arizona Public Services' acquisition of Four Corners units 4 and 5 on behalf of the Arizona Commission. That review included an examination of short-and long-term planning issues including environmental risk, fuel economics, transmission system capability, and demand and usage growth. Liberty's review also evaluated the various rate and revenue requirement impacts resulting from the acquisition.

Engagement Director for two Liberty audits for the Mississippi Public Service Commission of Mississippi Power Company's management and operation of fuel and purchased-power procurement. Responsible for reviews of fuel-oil and natural-gas contracting and management, including price-risk management, and the functioning of the Company's Fuel Cost Recovery and Energy Cost Mechanisms.

Engagement Director for Liberty's integrated work with New Hampshire Commission Staff on an analysis of the competitiveness of the Public Service New Hampshire's generating fleet. This work provided a valuation of the power plants, addressing current and expected energy market conditions, the effects of increased cycling of units designed for baseload operations, potential costs associated with compliance with current and potentially increased environmental restrictions, impacts on the competitive market place, and other factors important for the Commission to consider in determining what future role might exist for utility-owned supply resources.

Engagement Director for Liberty's review of electric system infrastructure, supply, and generation at Newfoundland Power and Newfoundland Hydro for the Board of Commissioners of Public Utilities.

Project Director and lead consultant for Executive Management and Governance and Human Resources on Liberty's management and operations audit of Pepco for the District of Columbia Public Service Commission.

Engagement Director for Liberty's review of Entergy Texas's exit from Entergy's multi-state, multi-operating company approach to system planning and operation; and systems planning changes needed to support stand-alone operation by Entergy Texas for the PUCT.

Engagement Director for Liberty's review of Pacific Gas & Electric use of risk assessment to drive electricity safety expenditures; included a review of the basis for identifying required programs, initiatives, and resources for the California Public Utilities Commission.

Project Director and lead consultant for Corporate Planning on Liberty's management and operations audit of Iberdrola SA/Iberdrola USA/NYSEG and RG&E for the New York Public Service Commission.

Project Director and lead consultant for Governance and Senior Management on Liberty's management and operations audit of Interstate Power and Light for the Iowa Utilities Board.

Project Director and lead consultant on Liberty's management and operations audit of the electricity, natural gas, and steam operations of ConEd for the New York Public Service Commission.

Project Director on Liberty's benchmarking analysis of Arizona Public Service for the Arizona Corporation Commission. This study covered a ten-year audit period and benchmarked Arizona Public Service's performance with the following metrics: Operational Performance, Cost Performance, Financial Performance, Affiliate Expenses, and Hedging & Risk Management.

Project Manager for Liberty's comprehensive, detailed affiliate relationships and transactions audit of Duke Energy Carolinas for the North Carolina Utilities Commission staff.

Project Manager for the performance of Liberty's audit for the Delaware Public Service Commission of a diagnostic audit of the affiliate costs borne by Delmarva Power, a member of the multi-state holding company, PHI. This review included an examination of the central services organization structure and operations, the procedures and methods used to allocate and assign costs, and test work to verify that execution of methods and procedures conforms to company procedures and to good utility practice.

Project Manager for Liberty's work for NorthWestern Energy to formulate long-range integrated infrastructure plans for its multi-state electric and natural gas distribution utilities. This project includes consideration of how to incorporate "Smart Grid" technology into infrastructure plans in a manner that will enable the Company to roll out new capabilities and services as technology makes them available, without undue acceleration of capital spending as uncertainties in this new marketplace become resolved.

Project Manager for Liberty's audit of Arizona Electric Power Cooperative for the Arizona State Corporation Commission which included reviews of fuel procurement and management, bulk electricity purchases and sales, power plant management, operations and maintenance, energy clause design and operation, and other issues affecting the prudence, reasonableness, and accuracy of costs that pass through the fuel and energy clause.

Project Manager for Liberty's audit of Southwest Transmission Cooperative for the Arizona Commission, a companion examination of the transmission cooperative that is owned and operated in parallel with Arizona Electric Power Cooperative (a generation cooperative). Among the issues examined in this audit were line losses.

Project Manager for Liberty's audit of Southwestern Public Service (SPS) for the New Mexico Public Regulation Commission that included a management review of the prudence of SPS' transactions under the Renewable Energy Credit tracker as conditionally approved by the Commission and a financial review of both revenues and expenses in order to provide an analysis of any under-recovery or over-recovery. Similarly, Liberty performed an evaluation of SPS' fuel clause process and regulations and a financial audit of fuel clause computation. In addition, reviews of purchases of coal, natural gas, oil, and purchased power, power plant operations, line losses, and cost allocation and assignment were also performed.

Project Manager for Liberty's audit of East Kentucky Power Cooperative, which included examinations of Governance, Planning, Finance, and Budgeting. Liberty performed for the Kentucky Public Service Commission an examination of governance at a generation and transmission cooperative serving 16 distribution cooperatives across the state. This study came in the wake of significant financial difficulties and also addressed planning, budgeting, financial, and risk functions and activities.

Project Manager for Liberty's audit for the Virginia State Corporation Staff of Potomac Edison Distribution System Transfer. Liberty examined the public interest questions associated with the transfer by an Allegheny Energy's utility operating subsidiary (Potomac Electric) of all of its electricity distribution operations business and facilities in Virginia to two rural electric cooperatives.

Project Manager for Liberty's audit of the fuel and purchased-power procurement practices and costs of Arizona Public Service Company for the Arizona Corporation Commission. Liberty completed audits relating to fuel procurement and management and on rate and regulatory accounting for related costs at Arizona Public Service Company for the Arizona Corporation Commission.

Project Manager for Liberty's audit of Duke Energy Carolinas for the North Carolina Utilities Commission. Scope included compliance with regulatory conditions and code of conduct imposed by the Commission after the merger with Cinergy, and affiliate transactions and cost allocation methods.

Project Manager for Liberty's audit of affiliate transactions of Nova Scotia Power on behalf of the Nova Scotia Utility and Review Board.

Project Manager for Liberty's audit for the New Jersey Board of Public Utilities of the competitive service offerings of the state's four major electric companies. Scope included corporate structure, governance, and separation, service company operations and charges, inter-affiliate cost allocations, arm's-length dealing with respect to a variety of code-of-conduct requirements, and protection of customer and competitor proprietary information.

Project Manager and witness for the staff of the Arizona Corporation Commission addressing the merits of the proposed acquisition of UniSource by a group of private investors.

Project Manager and witness before the Oregon Public Utility Commission addressing the merits of the proposed acquisition of Portland General Electric by a group of private investors.

Engagement Director for Liberty's provision of engineering and technical assistance to the Vermont Public Service Board in connection with review of public necessity and convenience related to the Northwest Reliability Project, which would add a major new 345kV transmission plan to provide an additional source of electricity to serve Vermont's major load growth in its northwest region. The project involved transmission reinforcements at lower voltages and significant substation upgrade work. The proceedings had numerous public, private, and government interveners, who raised issues regarding project need, available electrical alternatives, routing and design, and electromagnetic radiation.

Project Manager for Liberty's support for the New Hampshire Public Utilities Commission in its charge to oversee the divestiture of the Seabrook nuclear plant as part of a major restructuring settlement. The sale produced record high compensation for nuclear facilities in the country.

Project Manager and witness for Liberty's assessment of fuel procurement, affiliate transactions, and automatic adjustment clause implementation for the staff of the Nova Scotia Utility and Review Board in rate case of Nova Scotia Power.

Project Manager for Liberty's engagement on behalf of Boston Edison to examine the company's affiliate relations, including issues of the valuation of assets transferred to an affiliate.

Testified in proceedings before the Massachusetts Department of Telecommunications and Energy (formerly the Department of Public Utilities) on several telecommunications issues, including: (a) development of competition, and legislative and regulatory-policy changes supporting it, (b) electric-utility entry into telecommunications markets, (c) costs, prices, and market value of network elements, (d) requirements of the Telecommunications Act of 1996, (e) assessment of compliance with commission orders, company procedures, and service agreements regarding limits on affiliate interactions, (f) inter-company loans, guarantees, and credit support among utilities and their affiliates, (g) accounting for affiliate transactions, (h) obligations to allow nondiscriminatory access to network infrastructure to third parties, and (i) cost pools, overhead factors, and allocation of common costs among utility and non-utility affiliate activities and entities.

Project Manager for Liberty's major consulting engagement for the New Hampshire Public Utilities Commission. Liberty examined management, operations, and costs at Public Service Company of New Hampshire/Northeast Utilities, which is engaged in the operational and cost-accounting separation of its network into segments, for the purposes of restructuring service offerings to allow competition in certain aspects of electric-energy supply. This engagement included an assessment of valuations of nuclear and fossil units, as well as supply contracts with independent-power producers. Liberty also assisted in efforts to settle rate case and restructuring disputes involving, among other issues, stranded costs associated with power plants. The scope of Liberty's work included the development of plans and protocols for power plant (fossil, hydro, and nuclear) and power supply contract assets, as well as the oversight of activities associated with asset auctions.

Engagement Director for Liberty's evaluation of corporate relations and affiliate arrangements of Dominion Resources, Inc. and Virginia Power for the Virginia State Corporation Commission. This project addressed all significant aspects of corporate governance, operating relationships, and affiliate arrangements between the two entities.

Project Director for Liberty's evaluation of a report prepared by a consultant to the Hawaii Public Utilities Commission on the relationship between Hawaiian Electric Industries (HEI), a diversified utility-holding company, and Hawaiian Electric Company (HECO), its principal subsidiary and operating electric utility.

Project Director for all aspects of Liberty's comprehensive management and operations audit of West Penn Power Company for the Pennsylvania Public Utilities Commission. Managed focused reviews of the Company's affiliated costs, power dispatch and bulk power transactions, customer services, finance, and corporate services. Presented testimony before the PAPUC on behalf of the Office of Trial Staff regarding the results of the audit in West Penn's rate case.

Lead Consultant for affiliate relations for Liberty's assignment of providing assistance to Delmarva Power & Light Company in developing and implementing self-assessment and continuous-improvement processes.

Project Director for Liberty's reviews of fossil-fuel procurement and administration in Liberty's management/performance audits of the Centerior Energy Company's operating companies -

Cleveland Electric Illuminating Company and Toledo Edison Company - and Ohio Edison, Monongahela Power (an Allegheny Power System operating company), and Cincinnati Gas & Electric, for the Public Utilities Commission of Ohio.

Served as advisor to the administrative law judge of the Delaware PSC responsible for hearing cases regarding the implementation of the new law that restructures the electric-utility industry in Delaware.

Engagement Director for nuclear plant performance-improvement projects that Liberty conducted for Duquesne Light Company, Centerior Energy, Nebraska Public Power District, and Pennsylvania Power & Light Company (PP&L).

Engagement Director for a Liberty assignment for Florida Power Corporation, regarding a proposal by the Tampa Electric Company to construct transmission lines to serve the cities of Wauchula and Fort Meade, Florida. Liberty's testimony helped convince the Florida Public Service Commission that Tampa Electric Company's proposed line was uneconomic.

Directed Liberty's engagement to assist a regional electric generation and transmission cooperative, whose members' combined operations make it a major competitor in the state's electricity business, to conduct its first-ever comprehensive and formal strategic-planning process.

Natural Gas

Project Manager for Liberty's investigation of Peoples Gas of Chicago's Accelerated Main Replacement Program for the Illinois Commerce Commission.

Project Manager for Liberty's review of Connecticut's program to produce a major expansion of natural gas availability and use by all three of its natural gas utilities for the PURA.

Project Manager for Liberty's examination of safety programs and activities of NiSource's Maine subsidiary Northern Utilities for the Maine Public Service Commission.

Project Manager for Liberty's focused and general management audits of NJR, New Jersey Natural Gas, and affiliates for the New Jersey Board of Public Utilities. This project included detailed examinations of affiliate relationships, governance, financing and utility ring-fencing, compliance with New Jersey EDECA requirements for affiliate separation, protection of confidential information, non-discrimination against third-party competitors with utility affiliates, and other code-of-conduct issues. Personally performed the reviews of governance, EDECA requirements compliance, and legal services.

Project Manager on a major focused audit of Peoples Gas/Integrys that Liberty performed for the Illinois Commerce Commission. Audit topics included natural gas forecasting, portfolio design and implementation, gas purchase and sale transactions, controls, organization and staffing, asset management, off-system sales, storage optimization, and all other issues related to gas supply over a period of eight years.

Project Manager for Liberty's focused and general management audits of SJI, South Jersey Gas, and affiliates for the New Jersey Board of Public Utilities. This project included detailed examinations of affiliate relationships, governance, financing and utility ring-fencing, compliance with New Jersey EDECA requirements for affiliate separation, protection of confidential information, non-discrimination against third-party competitors with utility affiliates, and other code-of-conduct issues. Personally performed the reviews of governance, EDECA requirements compliance, and legal services.

Project Manager for Liberty's work with staff of the Virginia State Corporation Commission to evaluate the services of an affiliate providing gas portfolio management services under an asset management agreement with Virginia Natural Gas, an operating utility subsidiary of Atlanta-based AGLR.

Project Manager for Liberty's focused audit of NUI Corporation and NUI Utilities. This audit included a detailed examination of the reasons for poor financial performance of non-utility operations, downgrades of utility credit beneath investment grade, and retail and wholesale gas supply and trading operations. Also examined performance of telecommunications, engineering services, customer-information-system, environmental, and international affiliates. The audit included detailed examinations of financial results, sources and uses of funds, accounting systems and controls, credit intertwining, cash commingling, and affiliate transactions, among others. Liberty's examination included very detailed, transaction-level analyses of commodities trading undertaken by a utility affiliate both for its own account and for that of utility operations.

Project Manager for Liberty's comprehensive management audit of United Cities Gas Company for the Tennessee Public Service Commission. Responsible for the focused reviews of affiliate interests, executive management and corporate planning, and vehicle management.

Lead Consultant in Liberty's management audit of Connecticut Natural Gas Company for the Connecticut Department of Public Utility Control (DPUC). Responsible for reviews of organization and executive management and legal management.

Lead Consultant in Liberty's management audit of Southern Connecticut Gas Company for the DPUC. Responsible for organization and executive management, affiliates, and legal management. Included valuation of a major, rate-based LNG facility being offered for sale.

Directed Liberty's management audit of Yankee Gas Services Company for the DPUC.

Engagement Director for Liberty's evaluation of regulatory needs and alternatives for the Georgia Public Service Commission in regulating the state's local-gas-distribution companies in the aftermath of FERC Order 636.

Project Director for Liberty's review of gas-purchasing policies and practices at Pike Natural Gas Company and Eastern Natural Gas Company for the Public Utilities Commission of Ohio. Responsible for the review of organization and staffing and regulatory-management issues.

Combination Utilities

Engagement Director for Liberty's examination of the cost-allocation methods of Baltimore Gas & Electric Company and its affiliates for the Maryland Office of People's Counsel.

Project Director for Liberty's focused management audit of affiliate transactions of Public Service Electric & Gas Company (PSE&G) and the unregulated subsidiaries of Public Service Enterprise Group, Inc., the parent, for the New Jersey Board of Regulatory Commissioners. Task leader for the review of organization and planning, and executive management.

Project Director for Liberty's management and operations audit of New York State Electric & Gas Corporation for the New York Public Service Commission (NYPSC). Responsible for managing the review of corporate planning and organization, service centralization, specific corporate services, and finance and accounting.

Project Director for Liberty's management and operations audit of Central Hudson Gas & Electric Corporation for the NYPSC.

Telecommunications

Arbitrator named by the District of Columbia Public Service Commission to address industry-wide need for amendments to interconnection agreements as a result of the FCC's Triennial Review Order.

Project Manager for assistance being provided to the Administrative Law Judge of the Delaware Public Service Commission hearing the arbitration to address industry-wide need for amendments to interconnection agreements as a result of the FCC's Triennial Review Order.

Project Manager for Liberty's engagement to serve as advisors to commissioners of the District of Columbia Public Service Commission in their review of the Section 271 application of Verizon to provide in-region, interLATA service in the District.

Project Manager for Liberty's engagement to serve as advisor to the administrative law judge of the Delaware Public Service Commission in the review of the Section 271 application of Verizon to provide in-region, interLATA service in the state.

Retained by the Idaho Public Utilities Commission to serve as administrative law judge in complaint proceedings involving three paging companies and Qwest, involving a variety of financial disputes arising out of interconnection and tariff purchases.

Conducted wholesale performance metrics training for staff members and commissioners of the Pennsylvania Public Utility Commission as part of efforts to monitor service quality and payments under the Verizon Performance Assurance Plan adopted in connection with the RBOC's entry into the in-region inter-LATA market in Pennsylvania.

Engagement Director for Liberty's comprehensive financial review of Verizon New Jersey Inc. (VNJ) for the New Jersey Board of Public Utilities. The review had three parts: a financial evaluation; a review of merger costs and savings; and an assessment of affiliate costs and transactions.

Engagement Director for Liberty's audit of Ameritech-Ohio policies, procedures and compliance with service quality performance requirements under Ohio's Minimum Telephone Service Standards.

Engagement Director for Liberty's audit of Qwest's performance measures for the Regional Oversight Committee (ROC). Responsible for the evaluation of the processes and data tracking of several hundred wholesale and retail performance indicators including service areas such as provisioning, OSS access, maintenance and repair, and billing.

Project Manager and hearing administrator for Qwest's 271 hearings for the commissions of Idaho, Iowa, Montana, New Mexico, North Dakota, Utah, and Wyoming.

Engagement Director for Liberty's assistance provided to the Staffs of the Virginia State Corporation Commission and the New Jersey Board of Public Utilities in the implementation of the 1996 Telecommunications Act.

Project Manager for Liberty's assistance to Delaware PSC arbitrators in seven different interconnection cases arising out of the Telecommunications Act.

Served on an arbitration board in Mississippi, and as the sole arbitrator in two cases in Idaho regarding interconnection agreements between incumbent local-exchange companies and new entrants to the local telephone market.

Engagement Director for Liberty's work determining permanent prices for the unbundled-network elements of Southwestern Bell Telephone for the Oklahoma Corporation Commission.

Engagement Director for Liberty's provision of arbitration services to the North Dakota Public Service Commission and Nebraska Public Service Commission in cases involving implementation of the Telecommunications Act of 1996.

Engagement Director for Liberty's combined comprehensive management/affiliate-relations audit of Bell Atlantic - Pennsylvania for the PAPUC, and affiliate relations audit of Bell Atlantic - District of Columbia for the Public Service Commission (DCPSC) of the District of Columbia. Served as team leader with responsibility for the coordination of the review of executive management, finance, and support services.

Engagement Director for Liberty's examination of the accounting and allocation on lobbying costs of Bell Atlantic for an eight-year period for the DCPSC. Engagement included an examination of the propriety of policies and procedures for assigning and allocating lobbying costs.

Engagement Director for a management audit of GTE South, Inc. for the Kentucky Public Service Commission. This examination included a review of GTE's affiliate transactions.

Project Director for Liberty's evaluation of New York Telephone's transactions with affiliates for the NYPSC. Responsible for the review of affiliates involved in directories publishing, government affairs, international activities, information services, and the legal-affairs entity.

Project Director for Liberty's management audit of the affiliated interests of C&P Telephone of Maryland performed on behalf of the Maryland Public Service Commission.

Engagement Director for Liberty's two assignments for the DCPSC in reviewing Bell Atlantic - District of Columbia's construction-program planning and quality-of-service standards.

Other Companies

Set up and managed service and facilities section of the PP&L Regulatory Affairs Department. Counseled utility management on regulatory and legislative matters. Litigated rate related and facility construction proceedings before agencies and the courts.

Attorney for the PA PUC. Assigned as counsel to the Commission's Audit Bureau in developing a comprehensive management-audit system. Negotiated contracts for the first commission-ordered management audits in Pennsylvania. Revised Commission organization and practice to conform to regulatory-reform legislation.

Testimony

Arizona: Fuel audit, base costs of fuel and power supply adjustor of the state's largest utility, serving Phoenix and other areas of the state

Arizona: AEPCO Rate Case, fuel audit, base costs of fuel and power supply adjustor

Arizona: Proposed acquisition of a large electric and gas utility by a private equity firm

Florida: Transmission line construction necessity

Illinois: Prudence of fuel procurement and management by Central Illinois Power

Illinois: Cost and rate impacts of failure to meet good utility practice in T&D capital and O&M projects and activities of Commonwealth Edison

Illinois: Presentation to the full commission of the results of Liberty's investigation of an $8 billion accelerated gas main replacement program by the gas company serving Chicago

Maryland: Code of conduct issues involving Baltimore Gas & Electric

Maryland: Support of findings and conclusions of comprehensive management audit of a Verizon predecessor (C&P Telephone)

Massachusetts: Affiliate transactions of NStar (formerly Boston Edison)

New Hampshire: Restructuring of state's largest electric utility (Northeast Utilities subsidiary PSNH) including comprehensive valuation of generation assets (considering availability, costs, revenues)

New Hampshire: Proposed merger of Consolidated Edison and Northeast Utilities

New Hampshire: Proposed acquisition of Verizon wireline business in Vermont, New Hampshire and Maine by FairPoint Communications

New Hampshire: Divestiture of utility-owned generating fleet and securitization of stranded costs

New Jersey: In-camera and public presentations of assessments of: (a) consequences for a state gas utility of holding company financial reverses, and (b) results of a comprehensive audit of management and operations and of affiliate transactions

Newfoundland/Labrador: Assessment of management actions in generation, transmission, distribution, and customer service management leading to and in connection with major system outages.

Nova Scotia: Cost and rate impacts of fuel and purchased power procurement and management in multiple base rate cases and fuel adjustment mechanism audits since 2004

Nova Scotia: Addressing propriety of adoption, readiness for, and design of a fuel adjustment mechanism

Nova Scotia: Necessity and propriety of a proposed biomass cogeneration (electricity production and steam for paper manufacturing)

Nova Scotia: Utility revenue requirements associated with executive compensation, vegetation management, storm preparation and response, and fuel and energy management prudence

Oklahoma: UNE price proceedings

Oregon: Portland General Electric acquisition

Pennsylvania: Cost and rate impacts associated with findings of comprehensive management audit of West Penn Power Company

Tennessee: Support of findings and conclusions of comprehensive management audit

Texas: Proposed acquisition of the electric transmission and distribution utility serving Houston and other areas of Texas

Virginia: In-camera presentations regarding the results of an ongoing investigation into the source of an open feud between the boards and the senior executives of Virginia's largest energy utility and those of its holding company

Virginia: Pricing of unbundled telecommunications elements and terms of wholesale interconnection agreements

Numerous Qwest region state commissions: Before a number of state commissions in the Qwest region to address the status and results of Liberty's audit of performance measures and its reconciliation of the differences between Qwest and CLEC measurement of performance data.

Education

J.D., with academic honors, Dickinson School of Law
B.A., cum laude, Dickinson College

Richard Mazzini

Areas of Specialization

Management and regulatory audits; utility operations, including nuclear and other power production; power marketing and risk management; strategic planning; organization analysis and competitive re-structuring; project management; cost management; and tariff design and management.

Relevant Experience

The Liberty Consulting Group

Public Service Commission of New York – An operations audit of the staffing levels of each electric and gas utility.

Board of Commissioners of Public Utilities – Lead Consultant in Liberty's review of the prudence of management decisions and actions of Newfoundland and Labrador Hydro concerning Island outages experienced during the preceding two winters of 2013 and 2014. This project sought to determine the costs related to these decisions and actions.

Nova Scotia Utility and Review Board - Lead Consultant and witness on audits of procurement and management practices of Nova Scotia Power (leading reviews of power plant operations. Liberty has assisted the Nova Scotia Utility and Review Board in other reviews of Nova Scotia Power regarding storm outage and response, base cost of fuel cases, rate cases, and in various other proceedings.

Board of Commissioners of Public Utilities – Lead Consultant in Liberty's review of electric system infrastructure, supply, and generation at Newfoundland Power and Newfoundland Hydro.

Illinois Commerce Commission – Technical Director responsible for Liberty's reviews of program management as part of Liberty's investigation of Peoples Gas of Chicago's Accelerated Main Replacement Program.

Public Service Commission of New York – A management audit of Iberdrola SA/Iberdrola USA/NYSEG and RG&E. Assistant Project Manager for a 14-member Liberty consultant team.

Public Service Commission of New York – A management audit of Con Edison. Assistant Project Manager for a 13-member Liberty consultant team.

Iowa Utilities Board – Lead Consultant for the reviews of Electric Operations and Emergency Planning for Liberty's management and operations audit of Interstate Power and Light.

Arizona Corporation Commission - Consultant on Liberty's benchmarking analysis of Arizona Public Service. This study covered a ten-year audit period and benchmarked Arizona Public Service's performance with the following metrics: Operational Performance, Cost Performance, Financial Performance, Affiliate Expenses, and Hedging & Risk Management.

Maine Public Utilities Commission – Lead Consultant for the review and analysis of proposed new transmission project, the Maine Power Reliability Project (MPRP). Lead Consultant for economic analysis.

Public Service Commission of Maryland – Lead Consultant supervising the various auctions for procurement of power for Maryland's standard offer service (SOS) customers and support for the PSC in their analysis of new approaches to SOS supply.

Lead Consultant for Gas and Electric Infrastructure Improvement on Liberty's work for NorthWestern Energy to formulate long-range integrated infrastructure plans for its multi-state electric and natural gas distribution utilities. This project includes consideration of how to incorporate "Smart Grid" technology into infrastructure plans in a manner that will enable the Company to roll out new capabilities and services as technology makes them available, without undue acceleration of capital spending as uncertainties in this new marketplace become resolved.

Lead Consultant for Liberty's audit of Arizona Electric Power Cooperative for the Arizona State Corporation Commission which included reviews of fuel procurement and management, bulk electricity purchases and sales, power plant management, operations and maintenance, energy clause design and operation, and other issues affecting the prudence, reasonableness, and accuracy of costs that passing through the fuel and energy clause.

Lead Consultant for Liberty's audit of East Kentucky Power Cooperative, which included examinations of Governance, Planning, Finance, and Budgeting. Liberty performed for the Kentucky Public Service Commission an examination of governance at a generation and transmission cooperative serving 16 distribution cooperatives across the state. This study came in the wake of significant financial difficulties and also addressed planning, budgeting, financial, and risk functions and activities.

Lead Consultant for Liberty's audit for the Virginia State Corporation Staff of Potomac Edison Distribution System Transfer. Liberty examined the public interest questions associated with the transfer by an Allegheny Energy's utility operating subsidiary (Potomac Electric) of all of its electricity distribution operations business and facilities in Virginia to two rural electric cooperatives.

Management Audits

Public Service Commission of New York – An operational audit of Con Edison's reliability and emergency response planning and processes. Lead Consultant for corporate strategy and priorities, emergency planning and organization.

Federal Energy Regulatory Commission (FERC) – A review of the California ISO. Examined governance issues, operating procedures, transmission planning and analysis, organizational issues, interfaces with stakeholders and recommendations for the restructuring of the California market.

City of Seattle (Washington) – Review of the City's utility, commissioned by City Council and the Office of City Auditor, to analyze financial strategies, power market and risk management strategies and governance schemes. Lead Consultant for risk management.

St. Vincent Electricity Services, Ltd. – A management audit commissioned by the Board of Directors. Scope included generation, transmission, distribution, organizational assessment, safety, procurement and fuel.

New Jersey Bureau of Public Utilities – Evaluation of the gas supply and hedging programs of the four New Jersey gas distribution companies.

New York Power Authority – Consulting support for an internally sponsored audit of energy risk management functions.

Strategic Business Planning

Barbados Light & Power Company – Project Manager and Lead Consultant for a strategic planning initiative. Major areas of attention included new generation options, regulatory strategies, competitive threats, tariff design, new business opportunities, human resource issues, and planning processes.

Barbados Light & Power Company – Project Manager and Lead Consultant for the development of a model for the risk analysis of various new generation investments.

Electricité de France – Provided business planning and analysis services in the furtherance of the utility's wholesale and retail businesses. The work included research and analysis of potential gas partnerships, trading alliances and development of new retail markets throughout Europe.

SaskPower (Saskatchewan) – Project Manager and Lead Consultant for development of a strategic plan for the Power Production Business Unit. The project included asset valuation and optimization, transmission plans and strategies, efficiency improvement, market analysis and organizational options.

Omaha Public Power District – Project Manager and Lead Consultant for an extensive strategic business planning initiative. This multi-phase project spanned one year and included (1) asset evaluation, estimation of potential stranded costs and stranded cost mitigation strategies; (2) business growth strategies, including retail retention and expansion, new products and services, new utility businesses, wholesale marketing and bulk power trading; (3) corporate restructuring through the formation of four new business units; (4) organization design, including the creation of two new marketing organizations and a new trading floor; and (5) regulatory and legislative strategy development.

Omaha Public Power District – Project Manager and Lead Consultant for a follow-up analysis to the above project a year later to recommend added steps and course corrections. Provided new recommendations on organization design, customer service, stranded costs, energy marketing and trading initiatives, risk management, new business development, new products and services and strategic planning processes.

A large Canadian Provincial Electric Utility – Strategic planning and business support in the analysis of future generation and transmission options associated with a major new generation construction project.

Tennessee Valley Public Power Association - Project Manager and Lead Consultant for development of a comprehensive new business strategy that reinvented the Association for a competitive environment. Key elements of the plan included a new expanded focus on government relations and the influencing of public policy, as well as the creation of four newly created business units and business endeavors.

City Council of Los Angeles (California) - Advice to the Council on the strategic plans of its municipal electric utility. Conduct of a workshop for the Council and staff on restructuring and competitive issues. Review of power marketing alliance strategies.

Riverside Public Utilities (California) - Analysis of the potential to sell all or part of the utility. Development of a new business vision and strategy. Analysis of outsourcing and alliance possibilities. Development of a power supply alliance, including design of the venture, development of RFP, evaluation of bidders, selection of finalist and negotiations. Organizational design and implementation. Planning and project management support for activities leading to open access.

Lower Colorado River Authority – Consulting support for strategic review and development of alliance strategies. Facilitation of management workshop to develop strategic responses to key issues and to examine options for strategic alliances.

ElectriCities of North Carolina – Business simulations and strategic planning for the North Carolina Power Agencies.

ElectriCities of North Carolina – Analysis of the Carolina P&L – Florida Progress merger with resulting strategies and negotiations on behalf of ElectriCities.

4–County Electric Cooperative - Strategic planning support for the Chief Executive Officer and Board of Directors. Designed and facilitated a planning workshop for the Board of Directors and key managers. Followed up with subsequent action plan for the Board.

Project and Cost Management

Omaha Public Power District (OPPD) – Lead Consultant responsible for design and implementation of a cost management program for a major overhaul of the Fort Calhoun Station.

This $400 million project involved replacement of the two steam generators, pressurizer and reactor vessel head.

Power Marketing, Procurement and Risk Management

Public Service Commission of Maryland – Consultant supervising the various auctions for procurement of power for Maryland's standard offer service (SOS) customers and support for the PSC in their analysis of new approaches to SOS supply.

Electricité de France – Supporting services for the implementation of a large trading and marketing alliance in Europe, including reporting and control processes and training workshops for employees.

SaskPower - Project Manager and Lead Consultant for the expansion of the bulk power marketing program and creation of an energy trading floor. Work included extensive recommendations on corporate structure, organization, trading and marketing strategies, trading floor characteristics, management controls, risk management strategies, training, alliance building and external interfaces.

Public Service Commission of Maryland – Provided consulting support to the PSC in the approval of the settlement agreement relating to Standard Offer Service (SOS).

New Businesses

BGE Corporation (Constellation Nuclear Services) – Project Manager and Lead Consultant for the business analysis, planning, design and startup of a new subsidiary business for the client. The business, provision of nuclear related services to U.S. and international utilities, was successfully started in July 1999.

Electricité de France – Provided support in the planning, analysis, structure and negotiation of a large international energy trading and marketing alliance (EDF Trading, based in London).

Tennessee Valley Public Power Association – Project Manager and Lead Consultant for a survey and analysis of the Association's more than 150 member utilities. Produced an analysis with recommendations for the products and services that can best serve the members in a deregulated environment.

Municipal Electric Association (Ontario) – Project Manager and Lead Consultant for the development of a definitive business plan for a new power procurement business on behalf of the Association's more than 250 municipal electric utilities. Work included initial feasibility assessments followed by a complete actionable plan for the creation of the new organization, including structure, organization, staffing, financing, market analysis, contingency plans, product offerings and promotional strategies. The resulting new company became a reality in late 1997.

ENERconnect (Ontario) – Served as interim Vice President of Marketing and Customer Service for the startup of this new power procurement and services company. Project Manager and Lead

Consultant for the development of a detailed operational plan for startup. Assisted in all aspects of startup including organizational design, business strategies, product design and development and support to executive management and the Board.

ABB Energy Solution Partners – Consulting support for ESP-sponsored projects, including customer and project research, project structure, energy supply options, alliances and preparation of proposals. Included regulatory research and discussions in Nevada, Michigan, New Jersey and New York.

Ambient Corporation – Consulting support for strategic and tactical business planning for this startup firm specializing in power line communications (PLC), including development of commercialization plan and supporting management processes, support of business plan, product and service development, regulatory strategies and financing documentation.

PacifiCorp - Customer research with two groups of large industrial and commercial customers. Designed and managed interactive workshops to obtain their input, served as subject matter expert for the sessions, produced and presented comprehensive analyses of the results with strategic insights for the client's marketing initiatives.

T&D Support

Alberta Electric System Operator – Analysis of transmission loss methodologies for the Alberta market.

A large Canadian Provincial Electric Utility - Business planning support for the transmission business unit. Analysis of the business potential of new transmission opportunities. Analysis of U.S. transmission policies and their potential impact on a Canadian player in the U.S. markets.

Utility Management

Pennsylvania Power & Light Company - Served in a variety of management positions in a long career with the utility. Responsible for strategic business planning, rates, bulk power marketing, system operation, management of non-utility generation contracts, rate design, market research and contract negotiations with large customers. Key management roles in cost management, planning and scheduling for all Susquehanna nuclear station design, licensing, and startup activities including outage management.

Other Consulting Positions

Senior Vice President for ABB Energy Consulting, responsible for managing consulting engagements for a variety of U.S. and European energy firms.

Principal for Navigant Consulting, Inc., involved in numerous consulting engagements serving the electric utility industry in competitive initiatives.

Senior Vice President for the Washington International Energy Group, responsible for the firm's competitive positioning practice.

Education

M.S., Nuclear Engineering, Columbia University
B.E.E., cum laude, Villanova University

Registrations

Registered Professional Engineer – Pennsylvania

Memberships

Institute of Electrical and Electronics Engineers, American Nuclear Society

Bjarne Andersen

Areas of Specialization

Almost 40 years of experience in the field of HVDC systems. Numerous projects and many important technical papers resulting in significant impact on HVDC, SVC, and STATCOM technologies. Deep understanding of HVDC and FACTS system design and the interaction of these systems with the ac network has resulted in many new innovations and improvements to the technology. Work on 25 different HVDC projects, some 20 SVC projects, and 2 STATCOM projects. Project Development, Feasibility Studies and Optioneering, Project Planning, Preliminary Design, Project Scoping, Preliminary System Studies, Technical Specification, Technical and Commercial Tender Evaluation, Supervision of System Design and Implementation, Testing of Key Components, Construction, Installation, Commissioning, Maintenance, Troubleshooting, Fault Finding of HVDC schemes. Line Commutated Converter (LCC) and Voltage Sourced Converter (VSC) HVDC technologies.

Relevant Experience

Andersen Power Electronic Solutions Ltd.

Founded the independent consultant engineering company - Andersen Power Electronic Solutions Ltd. in September 2003. Highlights of this experience include:

- HVDC Expert for a client on the bipolar ±350kVdc, 2 x 300 MW Caprivi project in Namibia, Africa, which is the only commercial project to use a bipolar configuration with VSC HVDC overhead lines, *i.e.* a project very similar to the Maritime Link. Also the HVDC expert on the ±200kVdc 500 MW interconnection between the Republic of Ireland and UK.
- As an independent consultant, involvement in advising several clients in many aspects of HVDC and FACTS systems. Has written technical specifications for such systems and has undertaken the technical evaluation of proposed solutions from manufacturers. After contract award has been involved in the detailed review of the contractor's design engineering for four HVDC projects. Projects have included:
    - A VSC HVDC scheme for connection of a large wind farm project to the mainland HVAC grid in Scotland
    - Advising and providing training in HVDC for National Grid, UK
    - Providing assessment of electrical transmission project options for the New Zealand Regulator
    - Lifetime project involvement in a long distance OHL VSC HVDC scheme for interconnection in Africa, the first commercial project in the world with this technology
    - A large SVC for grid support
    - A VSC HVDC scheme for interconnection of Ireland and Britain

- A multi-terminal, multi-vendor VSC HVDC scheme in Scotland for the extension of the mainland grid infrastructure and the collection of power from offshore wind farms
- Numerous feasibility studies in the area of HVDC and FACTS
- Training in the areas of HVDC and FACTS.

Convenor for CIGRE B4-37, a working group focusing on VSC Transmission, which completed its work in 2004, and of CIGRE B4-39, a working group focusing on the integration in ac networks of large scale wind power, where the use of HVDC and power electronics can provide significant advantages. Chairman of CIGRE SC B4, HVDC and Power Electronics from 2008 to 2014, and started eight working groups in the area of HVDC grids during that time.

Alstom

26 years of experience at Alstom (now GE Grid) providing turnkey High Voltage Direct Current (HVDC) Schemes of all different configurations used to inter-connect asynchronous ac networks and/or to transmit power over long distance (*e.g.* from remote hydro generation to a load centre) and Reactive Power Controllers (Static Var Compensators (SVC)) and FACTS (Flexible AC Transmission Systems) solutions to enhance the capability of ac transmission systems. Industrial career with Alstom that started in the areas of design and development of HVDC including ac harmonic filtering, thyristor valves and system design, and provided a good basis for the overall design and optimization of HVDC converter stations, SVC and FACTS systems. Later directed the Engineering and R&D of HVDC and FACTS equipment and system designs within Alstom, and participated actively in the technical and commercial activities of many tenders and contracts. Have participated in on-site commissioning of HVDC systems. Positions and responsibilities included:

- 2002-2003 R&D Director - Responsibility for all R&D activities in Alstom T&D Power Electronic Activities /UK.
- 2000-2002 Technologies Director - Responsibility for Technical Strategy, Research and Auditing.
- 1991-2000 Director of Engineering - Responsibility for Company Engineering and Development activities.
- 1987 -1991 Manager Applications - Responsibility for Application Engineering in the fields of HVDC, SVC and Industrial Convertors.
- 1983-1987 Chief Engineer - Responsibility for overall co-ordination of all technical aspects of new HVDC schemes, and detailed design and development responsibility for all items of convertor station hardware, excluding thyristor valves and electronic controls.
- 1982 - 1983 Manager Instrument Transformer Division - Responsibility for design, development and manufacture of high voltage current transformers.
- 1980 - 1982 Project Manager - GIS surge arrester development project, involving technical leadership of a multi-disciplined project team and overall budget control.
- 1977 - 1980 HVDC Development Engineer - Involved initially with overvoltage studies and insulation co-ordination. Subsequently involved in ac harmonic filtering, reactive

power control and wider aspects of system development for High Voltage Direct Current and Static Var Compensation.

Professional Affiliations

Fellow of Institution of Electrical Engineers (IET), UK

- Past Chairman of 7th International Conference on AC-DC Power Transmission, 2001

Fellow of Institution of Electronic & Electrical Engineers (IEEE)

- Received the IEEE PES Uno Lamm Award in 2012 with the citation "For his visionary and leading contributions to improve HVDC technology through the dissemination and use of Voltage Sourced Converters"
- Past Member of several working groups (I5, I8, HVDC & FACTS)
- Member of the FACTS Award selection committee.

Honorary Member of CIGRE (International Council on Large Electrical Systems)

- Chairman of Study Committee B4 (HVDC and Power Electronics) from 2008 to 2014
- Received the 2008 CIGRE Distinguished Member Award
- Regular Member for UK on CIGRE SC B4, HVDC and Power Electronics from 2000 to 2006
- Past Convenor of WG B4-37, VSC HVDC Transmission
- Past Convenor of WG B4-39, Integration of Large Scale Wind Power using Power Electronics and HVDC
- Received the 2004 Technical Committee Award in recognition of outstanding contribution to the work of CIGRE Study Committee B: HVDC and Power

Education

Ph.D., High Voltage Technique, Technical University of Denmark
M.Sc., Electrical Power Engineering, Technical University of Denmark

Professional Registrations

Chartered Electrical Engineer, UK