Q. **Reference: Rates and Regulation Evidence**

Please provide copies of the current reliability studies related to the proposed interconnection of Muskrat Falls to the Island grid. (Rates and Regulation Evidence, page 4.7, lines 7-9)

A. Please see the attached document (NP-NLH-109 Attachment 1), Reliability & Availability Assessment of the HVdc Island Link - April 10, 2012, prepared by SNC-Lavalin as part of the Lower Churchill Project and as required by Hydro's System Planning department for the integration of the Lower Churchill Project into the Island Interconnected System.

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# Lower Churchill Project

# RELIABILITY & AVAILABILITY ASSESSMENT OF THE HVdc ISLAND LINK

**SLI Document No.: 505573-480A-47ER-0017-00**

**Nalcor Reference No.: ILK-SN-CD-8000-EL-SY-0004-01-B1**

**Date: 10-Apr-2012**

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# 1 INTRODUCTION

## 1.1 Overview of the System

This Report presents the results of the reliability and availability analysis carried out to determine the expected performance of the ±350 kV, 900 MW HVdc interconnection between Muskrat Falls and Soldiers Pond (Island Link) [1]. The Maritime Link between Bottom Brook and the Nova Scotia power system was not considered in this study. The results consider the performance of each element of the Island Link as well as the composite reliability of the complete link from Muskrat Falls to Soldiers Pond.

Figure 1-1 provides an overview of the project area.

The assessment considered only the Island Link from the ac bus at the converter station in Muskrat Falls to the ac bus at the Soldiers Pond converter station. The generation at Muskrat Falls, the 315 kV interconnection to Churchill Falls and the synchronous condensers at Soldiers Pond were not included in this assessment since their influence on the reliability of the link itself is considered to be negligible. The number and rating of the synchronous condensers at Soldiers Pond was determined from the steady-state and transient stability analyses and an economic assessment considering single contingency outages of equipment.

| SNC·LAVALIN | RELIABILITY & AVAILABILITY ASSESSMENT OF THE HVDC ISLAND LINK | Revision | | |
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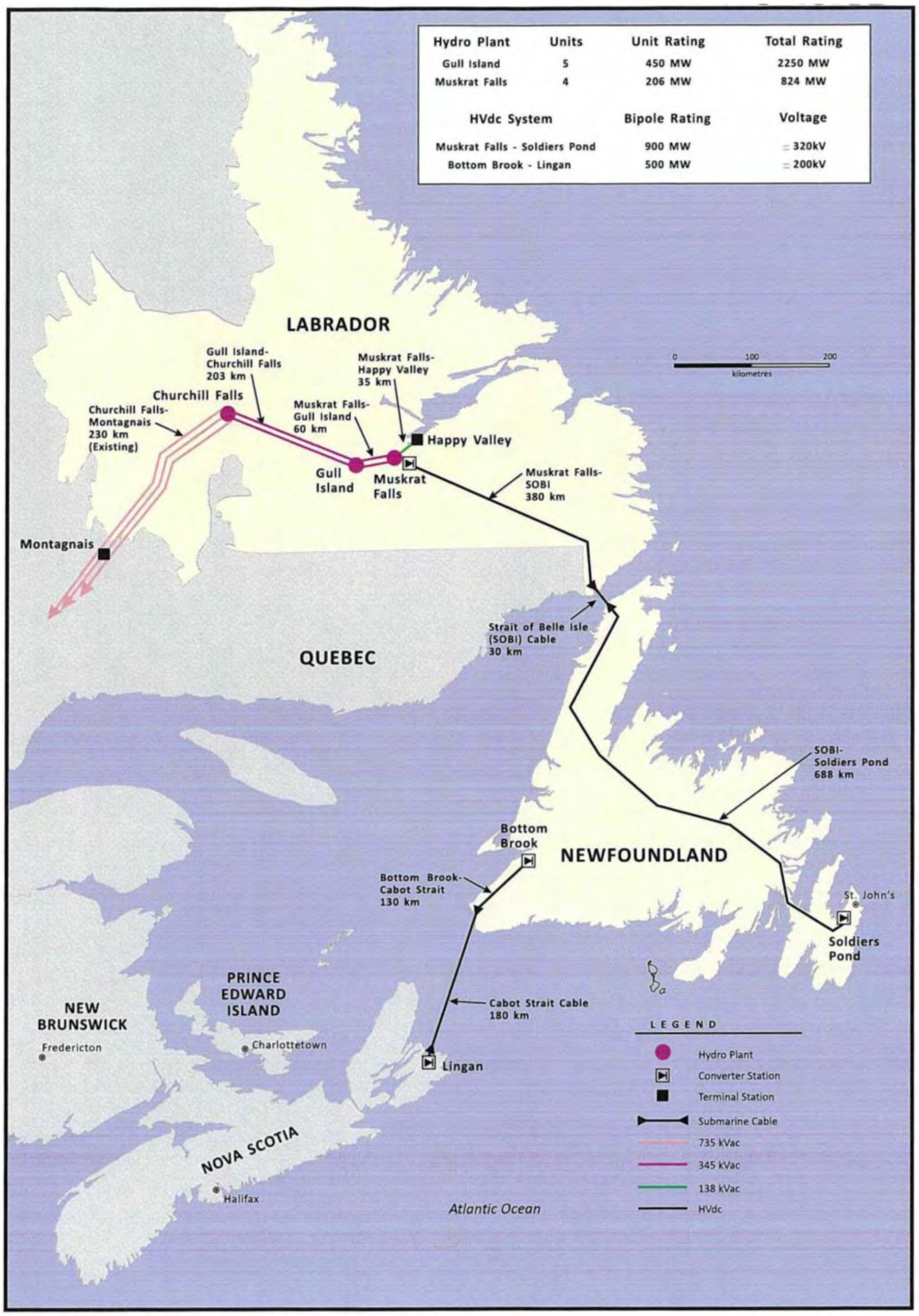
## Figure 1-1: Project Area Map



### 1.2 Objectives of the Studies

The objectives of this Reliability and Availability (R&A) Assessment are:

- To develop R&A performance indices for the converter stations
- To develop R&A performance indices for the HVdc transmission line from Muskrat Falls to Soldiers Pond
- To assess the R&A performance indices of the submarine cables from Forteau Point to Shoal Cove,
- To develop R&A performance indices for the electrode lines from Muskrat Falls to L'Anse au Diable and from Soldiers Pond to Dowden's Point
- To assess the improvements that could be made in the above indices considering design aspects such as the provision of spare equipment, over-rated equipment, etc.
- To assess the composite R&A performance indices of the complete HVdc Island Link from Muskrat Falls to Soldiers Pond

# 2 COMPONENT RELIABILITY

This section examines the reliability indicators available for the individual elements within the Island Link: HVdc converter stations, HVdc overhead line, HVdc transition compounds, HVdc submarine cables and electrode lines. An explanation of the reliability calculations used in this assessment is provided in Appendix A.

## 2.1 HVdc Converter Stations

A major input to this assessment was the information compiled by CIGRE on the performance of HVdc converter stations covering 158 terminal-years over the period 1988-2008[2] and the information contained in the PTI report R-64-81 [3]. For the 2-terminal, single-converter-per-pole stations, the following key performance indicators were determined:

- Forced Outage Rate (FOR) in %
- Forced Unavailability or downtime (FU) in hours/year

These indices are for the complete converter including valves, converter transformers, smoothing reactors, filters, etc. The following table summarizes the results, which are shown in detail in Appendix B:

**Table 2-1: Summary of FOR and FU (per terminal)**

| Period | Outage | FOR (%) | FU(hrs/yr) |
|---|---|---|---|
| 2007 | Pole | 0.15 | 13 |
| | Bipole | 0.0003 | 0.02 |
| 2008 | Pole | 0.38 | 34 |
| | Bipole | 0.0002 | 0.02 |
| 1988-2008 | Pole | 0.49 | 43.4 |
| | Bipole | 0.003 | 0.27 |

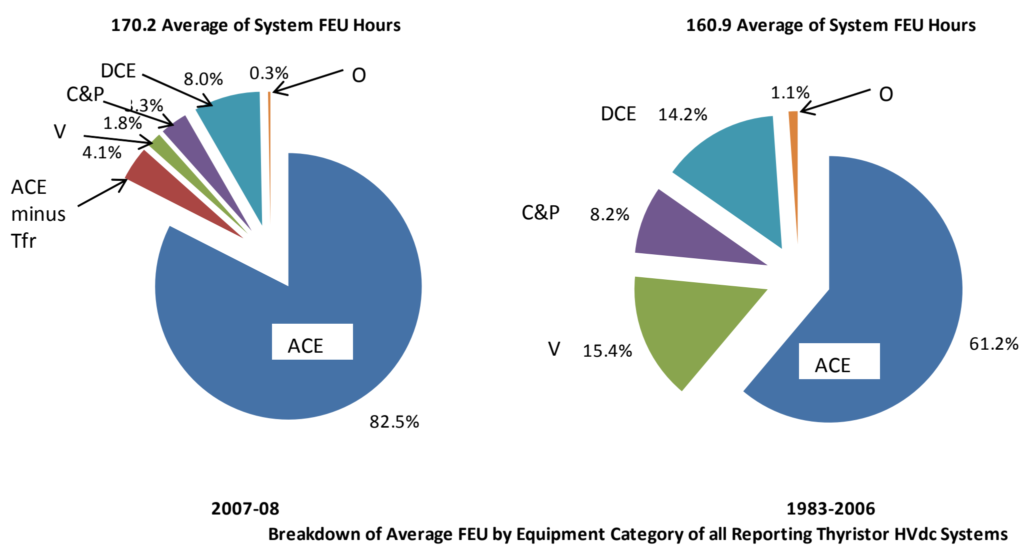
The average failure rate per terminal over the period 1988-2008 for pole outages was 2 failures/terminal/year; with an average repair time of 21 hours. The corresponding values for bipole outages were 0.2 failures/terminal/year and 1.3 hours.

Thus, for a 2-terminal bipole, the estimated average reliability indicators would be:

- 4 pole outages per year with a repair time of 21 hours per outage (FOR=0.98%)
- 0.4 bipole outages per year with a repair time of 1.3 hours per outage (FOR=0.006%)

The same source also provides information on the breakdown of forced energy unavailability (FEU) into the major components of a converter station: ac equipment and auxiliaries (ACE), thyristor valves (V), dc equipment (DCE), control & protection (C&P) and others (O) as shown in Figure 2-1.

**Figure 2-1: Forced Energy Unavailability (FEU) as reported by CIGRE**




The data for 2007-2008 indicate that the major contributors to the energy unavailability of the converter stations are the converter transformers, followed by the dc smoothing reactors. The provision of a spare unit for these major equipment items greatly improves the availability of the complete converter station, as shown in the following illustrative example.

**Spare Converter Transformer**

$\lambda$ = Failure rate (1-phase) = 0.01 f/yr

N = No. of Components = 6

$R_1$ = Repair Time (replacement with spare) = 168 hrs

$R_2$ = Repair Time at Factory = 4380 hrs

With no spare,

Average outage time per pole

= 0.01x3x4380 = 131 hrs/yr

With one spare (for 6 single phase units),

Effective outage time per outage

= $R_1+R_2/2 \times [N \lambda R_2/(8760+N \lambda R_2)]$ = 168+64 = 232 hrs

Average outage time per pole

= 0.01x3x232 = 7 hrs/yr

Almost all recent HVdc converter stations have been built with a spare transformer unit of each type and a spare smoothing reactor per terminal. The impact of this design measure is shown by the following CIGRE statistics:

**Table 2-2: Converter Unavailability**

| Item | | Performance Indicator | | |
|---|---|---|---|---|
| Spare Transformer | | No | Yes | Yes |
| Spare Smoothing Reactor | | No | No | Yes |
| Terminal | Unavailability | 3.04% | 0.94% | 0.21% |
| | Hours/ Year | 266 | 82.5 | 18.6 |

Based on the above information, it is recommended that a spare transformer unit of each type and a spare smoothing reactor be provided at each terminal of the Island Link. With spare units at each terminal, the reliability performance indicators of the converter stations can be taken as the average of the 2007 and 2008 statistics from Table 2-1 above since the most recent converter stations were designed with spare units.

**Table 2-3: Converter Reliability (Average 2007-2008)**

| Outage | FOR (%) | FU(hrs/yr) | F/yr | Repair Time (hrs) |
|---|---|---|---|---|
| Pole | 0.265 | 24 | 1.64 | 13.8 |
| Bipole | 0.00025 | 0.02 | 0.24 | 0.13 |

With the continuing improvements in the technology and design of converter stations, it would not be unreasonable to expect lower failure rates and repair times for the Muskrat Falls and Soldiers Pond converters. However, for the purpose of this analysis it was considered prudent to use the historical information from the recent past as this would give more conservative results. Insufficient information is available in the historical records to allow for a distinction to be made between each converter at either end of a dc link, one of which may be in a remote area. In the case of the Island Link, the Soldiers Pond converter will be located within a short distance of St. John’s, close to the Nalcor headquarters with easy access by road. The Muskrat Falls converter station is within easy access of Happy Valley but if repairs to any converter fault have to be made by staff mobilized from St. John’s, then significantly longer repair times would apply to the Muskrat Falls converter. For this assessment, the two converter stations are assumed to be identical.

## 2.2 HVdc Line

Transmission line outage statistics for HVdc lines are not as readily available as those for ac lines. However, the available outage data of selected projects are presented in Table 2-4 from a compilation of CIGRE statistics produced during the 1990’s to provide an indication of the performance of HVdc lines to date. The reporting periods indicated below are the numbers of years for which data was available and do not necessarily represent the total numbers of years in service for each line.

**Table 2-4: HVdc Transmission Line Outage Statistics**

| System | Length km | Reporting Period(yrs) | km-yrs | No. of Outages | f/100km /yr/pole | Avge Duration hrs |
|---|---|---|---|---|---|---|
| Pacific Intertie | 847 | 8 | 6,776 | 51 | 0.376 | 1.48 |
| Nelson River-1 | 960 | 11 | 10,560 | 45 | 0.213 | 0.53 |
| Nelson River-2 | 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 |

Using the averages from Table 2-4, for a route length of 1,100 km, the expected reliability performance would be:

- 2.101 outages per pole per year,
- With an average repair time of 1.78 hours per outage

This translates into an unavailability and FOR of 0.0425% per pole.

The common-mode failure of both overhead poles must also be taken into account. It is assumed that this type of failure mode is at least one order of magnitude less likely than a single pole failure but with a longer average repair time and is therefore assumed to have a failure rate of 0.02 f/100km/yr with an average repair time of 24 hrs.

## 2.3 HVdc Submarine Cable

There is even less information related to the reliability of submarine cables than for overhead dc lines. Cable installations of all types are generally considered to be very reliable since they are installed in a protected environment. However, in the case of submarine cables, the repair time for a cable fault can be extremely long since it involves the mobilization of a repair ship and recovery of the cable, which may not be feasible during certain seasons of the year. The submarine cable crossing of the Straits of Belle Isle is being designed with a spare cable to cover the loss of one cable. Each cable will be rated to carry the rated power of one pole continuously with a 5-minute overload capability of 2xrated power.

A report by C-Core [4] examined the incidence of iceberg strikes on the submarine cables and concluded that the expected failure rates for such events would be:

- 0.004 failures/year for a single cable
- 0.002 failures/year for 2 cables
- 0.001 failures/year for 3 cables

Repair times for cables in the Strait of Belle Isle could be very long and a repair time of 6 months (4,380 hours) has been assumed. Other cable failures, due to internal failures and other external causes, such as fishing and shipping activities, are assumed to be no worse than 1 in 50 years or 0.02 failures/year. Since there is a spare cable that can be quickly switched to replace a failed cable, the probability of losing a single pole due to a cable fault is the sum of the independent failure of 2 cables plus the probability of an iceberg strike affecting 2 cables. The independent failure of 2 cables can therefore be calculated by:

$F_C = \lambda_{C1}.U_{C2} + \lambda_{C2}.U_{C1} + \lambda_{C1\text{-}2}$
$U_C = U_{C1}.U_{C2} + U_{C1\text{-}2}$

Where $\lambda_{C1\text{-}2}$, $U_{C1\text{-}2}$ represents the failure rate and downtime of 2 cables due to an iceberg strike.

This evaluates to a failure rate of 0.00022 f/yr for the independent failure of 2 cables and 0.002 f/yr due to iceberg strikes, for a total failure rate of 0.0022 f/yr with an average repair time of 4,163 hrs/outage and an average downtime of 9.24 hours/year. This corresponds to an FOR of 0.105%.

For the complete loss of the link, either all 3 cables would need to fail due to independent failure events or an iceberg strike would need to affect all 3 cables. The independent failure mode evaluates to a very small value (9.9E-6 f/yr) and is considered insignificant, leaving a failure of 3 cables due to an iceberg strike as the remaining cause with a failure rate of 0.001 f/yr with an average repair time of 4,380 hours/outage and an average downtime of 4.38 hours/year (An FOR of 0.05%).

## 2.4 Electrode Line

An electrode line will be provided at each converter station to connect to a remote ground electrode. These lines, under bi-pole mode, will carry only the unbalance current between the two poles of the dc line but will also be used at 150% rated pole current during mono-polar operations involving ground return. These lines are essentially medium voltage lines with 2 conductors for redundancy in case of conductor failure and will be continuously monitored for integrity. At the Muskrat Falls end, the electrode line is 400 km in length and at the Soldiers Pond end; it is only 10 km in length.

CEA statistics on transmission equipment performance for ac lines up to 110 kV indicate the average failure rate for such lines to be 5 outages/100km/year with an average repair time of 8.2 hours (downtime = 41 hours/100km/year, 0.47%). Using these values for the Muskrat Falls electrode line would result in 20 outages/year. This appears to be a high value for a line that is continuously monitored and that spends most of its time operating at a voltage well below its rated value. Accordingly, a failure rate equal to one-tenth of this value (i.e. 0.5 failures/100km/year) was assumed and the repair time was kept at 8.2 hours per outage.

For the common-mode failure of both circuits of the electrode line, a failure rate one order of magnitude lower was assumed (i.e. 0.05 failures/100km/year) and the repair time was taken to be the same as for the common-mode failure of both poles of the bipole (i.e. 24 hours). Even with both circuits of the electrode line out of service, it will still be possible to operate the link at rated power with the unbalance current being handled by the station ground or, at worst, running at reduced power in mono-polar mode using metallic return.

The electrode line at the Muskrat Falls end (400 km) will either be constructed on a separate wood-pole line or will be installed on the towers of the main dc line itself. It would be reasonable to expect the reliability of the electrode line to be improved if it is mounted on the main line since the majority of common-mode failure events associated with the main line would be the same common-mode failure events associated with the electrode line. Thus the common-mode failure of the two electrode line circuits is already included in the common-mode failure of the bipole. The impact of this is, however, relatively small.

Given the above considerations, it is considered that the reliability related to the complete loss of the Island Link will not be significantly influenced by the reliability of the electrode lines at either terminal.

# 3 COMPOSITE SYSTEM

The composite system reliability of the Island Link can be determined from a consideration of the reliability of the components of the system. The actual connection diagram of the Island Link together with the corresponding connection diagram for the individual components of the reliability is shown in Figure 3-1. The individual poles of the bipole (L1+C+L2) and the converters (CP) are shown as parallel elements since both must fail for the link to fail, while the common-mode failure of the bipole due to a converter fault (BPC or cable/line fault (BPL1, C3 and BPL2) are shown as series elements since any of these failures will result in failure of the link. In all the results tables that are presented in the following sections, the results have been rounded to the appropriate number of significant digits. However, in the actual calculations, the full number of decimal places was retained to ensure the overall arithmetic accuracy of the results.

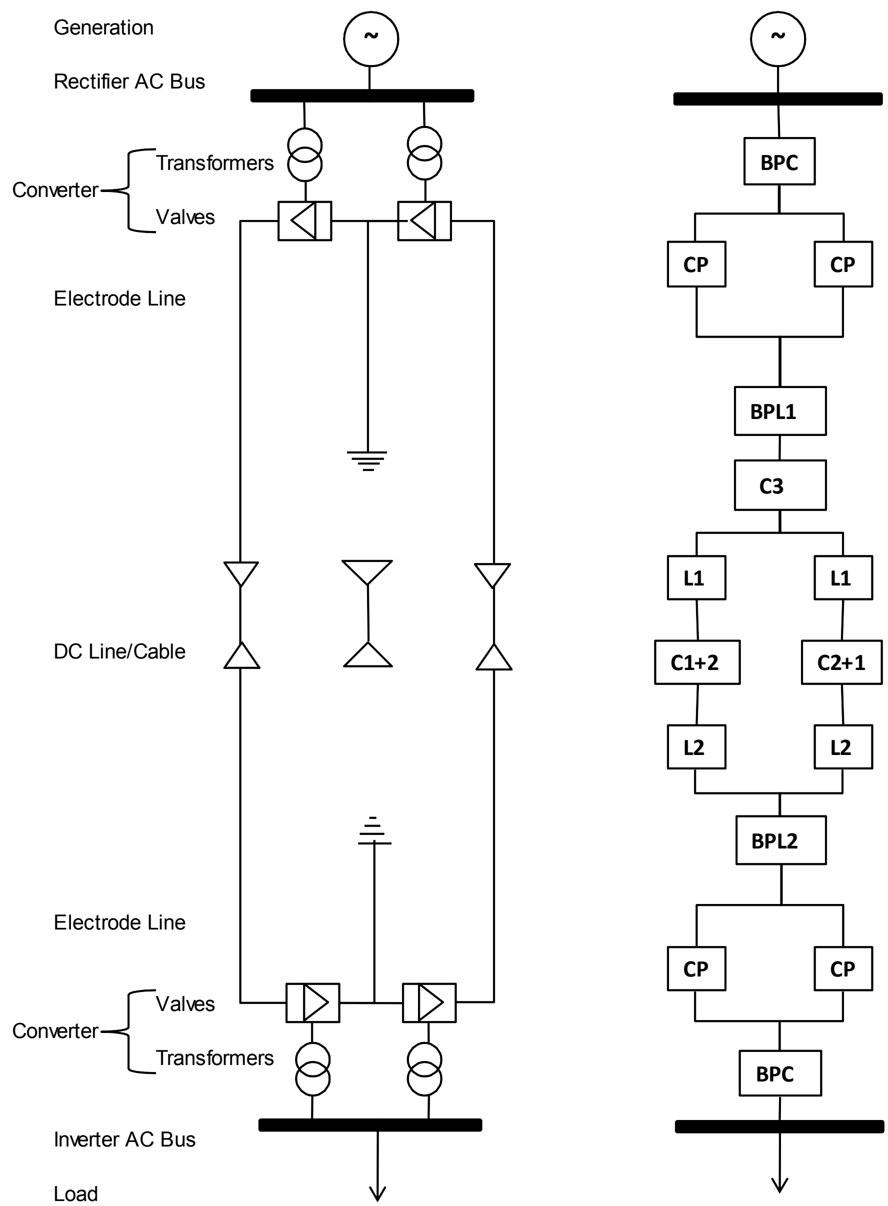
## 3.1 HVdc Overhead Line and Submarine Cable

First, it is necessary to determine the composite reliability indices associated with each parallel pole element (L1, C1+2, and L2 in series). Since the failure of any one of these elements will result in the failure of one pole, the failure rate and unavailability of each element can simply be added together as shown in Table 3-1. For each element, the downtime (or unavailability) is the product of the failure rate and the repair time ($U=\lambda.r$). Once the total failure rate and downtime have been determined, the repair time can be calculated as $r=U/\lambda$. For the submarine cable, the failure rate, repair time and downtime are those associated with the independent failure of 2 cables and an iceberg strike that impacts 2 cables.

**Table 3-1: Reliability Performance of One Pole of the HVdc Line**

| Element | Failure Rate (f/yr) | Repair Time (hrs) | Downtime (hrs/yr) |
|---|---|---|---|
| L1-388 km | 0.741 | 1.78 | 1.32 |
| C-Submarine cable | 0.0022 | 4,163 | 9.24 |
| L2-680 km | 1.3 | 1.78 | 2.31 |
| **Total** | 2.042 | 6.3 | 12.87 |

## Figure 3-1: Island Link Reliability Connection Diagram




| | |
|---|---|
| BPC | Common-mode Bipole Converter Outage |
| CP | Converter Pole Outage |
| BPL1 | Labrador Common-mode Outage of both Poles |
| L1 | Labrador Line Outage of One Pole |
| C1+2/C2+1 | 2-Cable Submarine Cable Outage |
| C3 | 3-Cable Submarine Cable Outage |
| L2 | Newfoundland Line Outage |
| BPL2 | Newfoundland Common-mode Outage of both Poles |

The reliability indices for the coincident, independent failure of two poles in parallel are given by:

$$\lambda_T = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{8760} \; f/yr$$

$$r_T = \frac{r_1 r_2}{r_1 + r_2} \; hrs$$

$$U_T = \lambda_T r_T \; hrs/yr$$

From the above composite reliability of each pole, the composite reliability of both poles in independent failure mode is:

$\lambda_T = (2.042)^2.(2x6.3)/8760 = 0.006$ f/yr

$r_T = (6.3)^2/(2x6.3) = 3.15$ hrs

$U_T = 0.006x3.15 = 0.019$ hrs/yr

In addition, for the complete failure of the link, the probability of an iceberg strike impacting all three submarine cables and the probability of a common mode outage of both overhead line sections must be added to the above independent, coincident failure of both poles.

### 3.2 Converters

Similarly, the coincident failure of both converters in independent mode can be calculated as:

$\lambda_T = (1.64)^2.(2x13.8)/8760 = 0.0084$ f/yr

$r_T = (13.8)^2/(2x13.8) = 6.9$ hrs

$U_T = 0.0086x7 = 0.06$ hrs/yr

### 3.3 Electrode Lines

As mentioned above, the link can still be operated at full power or reduced power even for the complete loss of the electrode line at either end of the link. As such, the reliability of the electrode line is considered to have no significant impact on the composite reliability of the link.

### 3.4 Complete System

For the failure of both lines/cables (P1+P2) or both converters (CP+CP), in series with the common-mode failure of both poles due to converter faults (BP) and main line faults (BPL1 and BPL2), the composite reliability of the Island Link is as shown below.

**Table 3-2: Composite Island Link Bi-pole Reliability**

| Element | Failure Rate (f/yr) | Repair Time (hrs) | Downtime (hrs/yr) | % of Total |
|---|---|---|---|---|
| BP-Muskrat Falls | 0.24 | 0.13 | 0.031 | 0.3 |
| CP+CP-Muskrat Falls | 0.0084 | 6.86 | 0.057 | 0.6 |
| BPL1-388 km | 0.074 | 24 | 1.776 | 18.6 |
| P1 + P2 | 0.007 | 621.7 | 4.479 | 46.9 |
| BPL2-680 km | 0.13 | 24 | 3.12 | 32.7 |
| CP+CP-Soldiers Pond | 0.0084 | 6.86 | 0.057 | 0.6 |
| BP-Soldiers Pond | 0.24 | 0.13 | 0.031 | 0.3 |
| **Total** | 0.7078 | 13.49 | 9.551 | 100 |

The composite, forced unavailability and FOR is therefore 9.551 / 8760 x 100 = 0.109%.

It is clear from the above results that the major contributors to the unavailability of the Island Link are the common-mode failure of both poles of the overhead line (representing nearly 52% of the total unavailability) and the independent, coincident failure of both poles for the overhead and submarine cable sections (representing 47% of the total unavailability). Of all the values used for the component reliability, the reliability indices associated with common-mode bipole and submarine cable failures are probably the least certain given the relatively small database of operating experience. The parameter that has the most influence on the overall unavailability due to these failures is the repair time required to return a bipole or submarine cable to service after a common-mode failure. The value used in the above analysis was based on the limited operating experience available worldwide which includes bipolar lines of similar length to the Island Link in remote areas with difficult access.

The implied availability from this result is 99.89%. However, it should be borne in mind that this availability value includes periods of time when the full capacity of the link is unavailable. For a pole outage or converter outage or during scheduled maintenance, the link will be operated in mono-polar mode at a power level up to 150% of rated power per pole on a continuous basis.

### 3.5 Reduced Power Operation

The scheduled maintenance would typically be of the order of 3 days per pole per year, assuming that maintenance work would be carried out at both terminal stations and on each line (pole) at the same time. With respect to forced periods when the Island Link will not be available for full power transmission, it is necessary to consider only those single contingency events that will result in the loss of one pole of the Island Link. These comprise the loss of a converter at either end or the permanent outage of either pole of the main dc line. Using the values from Table 2-3 for the converters and Table 3-1 for the overhead line and submarine cable components, Table 3-3 shows the reliability indices associated with reduced power modes.

**Table 3-3: Reduced Power Capability Modes (Mono-polar)**

| Element | Failure Rate(f/yr) | Repair Time(hrs) | Downtime(hrs/yr) |
|---|---|---|---|
| Scheduled Maintenance | 2.0 | 72 | 144 |
| Converter-Muskrat Falls | 1.64 | 13.8 | 22.42 |
| Pole 1 | 2.04 | 6.3 | 12.87 |
| Pole 2 | 2.04 | 6.3 | 12.87 |
| Converter-Soldiers Pond | 1.64 | 13.8 | 22.42 |
| **Total** | 9.36 | | 214.6 |

The composite unavailability and FOR is therefore 214.6 / 8760 x 100 = 2.45%.

Thus, the actual availability of the Island Link at full power capacity is 100-0.109-2.45 = 97.44%.

If the use of the station ground for mono-polar operation is not allowed in the event of the loss of the electrode line, the above values will be increased slightly due to the failure of both conductors of the electrode line. Only the loss of the Muskrat Falls electrode line will be significant since the length of the Soldiers Pond electrode line is relatively short. The coincident failure of both conductors of the Muskrat Falls electrode line was estimated at 0.2 failures/year with an average repair time of

24 hours and a downtime of 4.8 hours/year. If these values are added to those shown in Table 3-3 above, the resulting overall FOR increases from 2.45% to 2,51%.

The impact of the repair time for the common-mode failure of both circuits of either the Muskrat Falls electrode line or the main dc line is dominant to the point where the total forced unavailability can be approximated as being proportional to the repair time for such an event. Varying the fault repair time over the range of 3 hours to 10 days, with all other component reliability indices being held constant, the total forced unavailability in % is approximately 2.5/1000 x bi-pole repair time in hours. If a specific reliability performance is required (e.g. total forced unavailability ≤ 0.5%), then the repair time for a bi-pole line fault must be kept within 192 hours (8 days). This strong correlation between the unavailability of the link and the repair time associated with common-mode failures of both poles of the main dc line allows the desired reliability to be associated with target repair times. The unavailability of the link at full power, due to single pole forced outages or maintenance, is shared equally by the repair time for one pole and the time required for pole maintenance.

# 4 CONCLUSIONS & RECOMMENDATIONS

Objective 1: To develop R&A performance indices for converter stations

Using historical information compiled by CIGRE from HVdc installations throughout the world over the period 1988-2008, failure rates and repair times were estimated for the converter stations at each end of the Island Link.

**Table 4-1: Converter Reliability (Average 2007-2008)**

| Outage | FOR (%) | FU(hrs/yr) | F/yr | Repair Time (hrs) |
|---|---|---|---|---|
| Pole | 0.265 | 24 | 1.64 | 13.8 |
| Bipole | 0.00025 | 0.02 | 0.24 | 0.13 |

Objective 2: To develop R&A performance indices for the HVdc transmission line from Muskrat Falls to Soldiers Pond

- To assess the improvements that could be made in the above indices considering design aspects such as the provision of spare equipment, over-rated equipment, etc.,
- To assess the composite R&A performance indices of the complete HVdc Island Link from Muskrat Falls to Soldiers Pond.

**Table 4-2: Reliability Performance of the HVdc Line**

| Element | Failure Rate (f/yr) | Repair Time (hrs) | Downtime (hrs/yr) |
|---|---|---|---|
| L1-388 km | 0.741 | 1.78 | 1.32 |
| C-Submarine cable | 0.0022 | 4,163 | 9.24 |
| L2-680 km | 1.3 | 1.78 | 2.31 |
| **Total** | 2.042 | 6.3 | 12.87 |

The associated FOR is 0.147%.

**Table 4-3: Composite Island Link Reliability**

| Element | Failure Rate (f/yr) | Repair Time (hrs) | Downtime (hrs/yr) | Downtime % of Total |
|---|---|---|---|---|
| BP-Muskrat Falls | 0.24 | 0.13 | 0.031 | 0.3 |
| CP+CP-Muskrat Falls | 0.0084 | 6.86 | 0.057 | 0.6 |
| BPL1-388 km | 0.074 | 24 | 1.776 | 18.6 |
| P1 + P2 | 0.007 | 621.7 | 4.479 | 46.9 |
| BPL2-680 km | 0.13 | 24 | 3.12 | 32.7 |
| CP+CP-Soldiers Pond | 0.0084 | 6.86 | 0.057 | 0.6 |
| BP-Soldiers Pond | 0.24 | 0.13 | 0.031 | 0.3 |
| **Total** | 0.7078 | 13.49 | 9.551 | 100 |

The associated FOR is 0.109%. The availability is therefore 99.89%.

**Table 4-4: Reduced Power Capability Modes**

| Element | Failure Rate(f/yr) | Repair Time(hrs) | Downtime(hrs/yr) |
|---|---|---|---|
| Scheduled Maintenance | 2.0 | 72 | 144 |
| Converter-Muskrat Falls | 1.64 | 13.8 | 22.42 |
| Pole 1 | 2.04 | 6.3 | 12.87 |
| Pole 2 | 2.04 | 6.3 | 12.87 |
| Converter-Soldiers Pond | 1.64 | 13.8 | 22.42 |
| **Total** | 9.36 | | 214.6 |

The associated unavailability is 0.81% due to the forced outage of one pole and 1.64% due to the scheduled maintenance outage of a pole. If the station ground cannot be used for mono-polar operation when the Muskrat Falls electrode line is also unavailable, the total FOR will increase from 2.46% to 2.51%.

## 4.1 Conclusions

The provision of a spare transformer of each type and a spare smoothing reactor at each converter station will significantly improve the availability of the converters. This has become common practice in recent HVdc schemes.

Using representative reliability data from existing HVdc installations throughout the world, the overall forced unavailability of the complete Island Link is predicted to be approximately 0.1%. The forced unavailability of the full power capability of the Island Link is predicted to be less than 2.5%, with the scheduled unavailability for maintenance being 1.64%. However, both of the values for forced unavailability are very dependent on the average repair time that can be achieved for pole outages and common-mode failures of both poles of the dc line.

It has been shown that a linear relationship exists between these repair times and the unavailability of the Island Link. Once a target reliability has been decided on, the maximum repair time can be determined. The overall unavailability of the complete link is not sensitive to the repair time for the submarine cables. This is due to the provision of a spare submarine cable across the Strait of Belle Isle and the subsequent very low failure rates for 2 or 3 cables. An increase in the repair time for a common-mode failure of both overhead line sections of the dc line (due to a tower failure, for example) from 24 hours to 2 weeks (336 hours) resulted in an increase in the total unavailability from 0.108% to 0.835%.

Based on the historical data available, the repair time for single pole outages on the overhead line sections was estimated at 1.78 hours/outage, while the repair time for common-mode failure of both poles was assumed as 24 hours. If both these repair times are varied then the overall unavailability will change. The following values of overall FOR were calculated for a range of overhead dc line section repair times (these repair times were used for both independent, coincident failures of both poles and for the common-mode failure of both poles).

**Table 4-5: Variation in Overall FOR with DC Overhead Line Repair Time**

| Repair Time(hrs) | FOR(%) |
|---|---|
| 24 (1 day) | 0.112 |
| 48 (2 days) | 0.179 |
| 72 (3 days) | 0.251 |
| 96 (4 days) | 0.33 |
| 120 (5 days) | 0.416 |
| 144 (6 days) | 0.507 |
| 168 (1 week) | 0.605 |
| 336 (2 weeks) | 1.463 |

The relationship is not linear, as may be expected, but does show the dependence of the unavailability on the repair time associated with overhead dc line section faults.

The total unavailability of full power due to a pole outage is determined to a large extent by the scheduled maintenance outage of each pole.

## 4.2 Recommendations

At each converter station, a spare converter transformer of each type (single phase) and a spare smoothing reactor should be provided. This will significantly improve the availability of the converters.

Other critical components and those items with long lead times should also be considered as items that should be provided with on-site spares. These items are normally determined by the converter supplier in order to meet the specified target reliability and availability values in the converter specification.

# 5 REFERENCES


1) Nalcor Energy-Lower Churchill Project, :Basis of Design, Document LCP-PT-ED-0000-EN-RP-0001-O1.

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3) Newfoundland & Labrador HVDC Project, HVDC Link Reliability Studies, Power Technologies Inc., Schenectady, NY, Report R-64-81, 11 October, 1981.

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# APPENDIX A

# RELIABILITY FORMULAE

## Individual Components

The reliability of any individual component of a system can be expressed in terms of its failure rate (λ), repair time (r), availability (A) and unavailability or downtime (U). These indices are linked in the following relationships:

$U = \lambda \,.\, r$

$A = (1-U)$

The failure rate is normally expressed in the number of failures/year, the repair time is normally expressed in hours/repair, availability and downtime are normally expressed in hours/year or in per unit/year where the repair time is divided by 8760 hours/year.

Thus a component with a failure rate of 2 failures/year and a repair time of 24 hours/repair will have a downtime of 2 x 24 = 48 hours/year or 48/8760 = 0.0055 p.u./year (sometimes expressed as 0.55%).

Furthermore, the forced outage rate (FOR) can be calculated as:

$\mathbf{FOR} = \frac{\mathbf{U}}{1+\mathbf{U}}$ , which can be approximated as FOR = U where U is small in relation to unity.

## Components in Series

In a system where the failure of any single component will result in failure of the system, the components are said to be connected in series, using the analogy of an electrical circuit. In such a system, the total system failure rate is simply the sum of the failure rates of the individual components. Similarly, the downtime of the system is the sum of the downtimes of the components.

For example if a system comprises two components, one with a failure rate of 2 failures/year and a downtime of 24 hours/year (repair time = 24/2 = 12 hours/failure); the other with a failure rate of 3 failures/year and a downtime of 12 hours (repair time = 12/3 = 4 hours/failure), the system failure rate will be 5 failures/year with a total downtime of 36 hours/year (repair time = 36/5 = 7.2 hours/failure).

**Components in Parallel**

In a system where multiple components must fail to result in failure of the system, the components are said to be connected in parallel, again using the analogy of an electrical circuit. For a two component system, two possible failure modes can be envisaged: the failure of component 2 while component 1 is in a failed state and the failure of component 1 while component 2 is in a failed state. This is expressed mathematically as follows:

$$\lambda_T = \lambda_2 . \mathbf{U}_1 + \lambda_1 . \mathbf{U}_2 = \lambda_2 . (\lambda_1 . \frac{\mathbf{r}_1}{8760}) + \lambda_1 . (\lambda_2 . \frac{\mathbf{r}_2}{8760}) = \frac{\lambda_1 . \lambda_2 . (\mathbf{r}_1 + \mathbf{r}_2)}{8760} \ \textbf{failures / year}$$

The total downtime is simply the product of the individual downtimes.

$U_T = U_1 . U_2$

From which the average repair time can be calculated as:

$$\mathbf{U_T} = \lambda_1 . \mathbf{r}_1 . \lambda_2 . \mathbf{r}_2$$

$$\mathbf{r_T} = \frac{\mathbf{U_T}}{\lambda_T} = \frac{\lambda_1 . \mathbf{r}_1 . \lambda_2 . \mathbf{r}_2}{\lambda_1 . \lambda_2 . (\mathbf{r}_1 + \mathbf{r}_2)} = \frac{\mathbf{r}_1 . \mathbf{r}_2}{\mathbf{r}_1 + \mathbf{r}_2} \ \textbf{hours / failure}$$

Using the same example used for components in series:

$$\lambda_T = \lambda_2 . \mathbf{U}_1 + \lambda_1 . \mathbf{U}_2 = 3 \, \mathbf{x} \, 24 / 8760 + 2 \, \mathbf{x} \, 12 / 8760 = 0.011 \ \textbf{failures / year}$$

$$\mathbf{U_T} = \mathbf{U}_1 . \mathbf{U}_2 = 24 \, \mathbf{x} \, 12 / 8760 = 0.033 \ \textbf{hours / year}$$

$$\mathbf{r_T} = \frac{4 \, \mathbf{x} \, 12}{4 + 12} = 3 \ \textbf{hours / failure} \ \textbf{or} \ \mathbf{r_T} = \frac{\mathbf{U_T}}{\lambda_T} = \frac{0.033}{0.011} = 3 \textbf{hours / failure}$$

# APPENDIX B

# CIGRE HISTORICAL DATA 1988-2008

## CIGRE Historical Data 1988-2008 per Terminal

2 Terminal Systems - 1 Converter per Pole

| Name | 2007 | | | | 2008 | | | | Average 1988-2008 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pole | | Bipole | | Pole | | Bipole | | Years | Pole | | Bipole | |
| | fp | dp | fb | db | fp | dp | fb | db | | fp | dp | fb | db |
| Skagerrak 1 & 2 | 1.25 | 3.1 | 0 | 0 | 2 | 3.8 | 0.5 | 1 | 20 | 1.54 | 17.1 | 0.13 | 1.03 |
| Square Butte | 1 | 4.1 | 1.5 | 0.3 | 5.25 | 0.8 | 0 | 0 | 18 | 2.85 | 6.2 | 0.42 | 2.27 |
| CU | 0.5 | 23.8 | 0 | 0 | 1.25 | 58.5 | 0 | 0 | 20 | 1.71 | 4.6 | 0.28 | 1.66 |
| Gotland 2&3 | 0.25 | 0.8 | 0 | 0 | 0.5 | 46.6 | 0 | 0 | 20 | 0.38 | 35.8 | 0.2 | 1.49 |
| Fennoskan | 2 | 14.2 | | | 1.5 | 46.4 | | | 19 | 2.26 | 10.1 | | |
| SACOI | 3.33 | 1.7 | | | 1.67 | 2.5 | | | 16 | 4.9 | 2.6 | | |
| New Zealand 2 | 2.5 | 4.3 | | | 0.5 | 0.7 | | | 17 | 1.65 | 2.7 | | |
| Kontek | 0.5 | 2.7 | | | 1 | 32 | | | 7 | 0.86 | 15.7 | | |
| SwePol | 0.5 | 2.4 | | | 2 | 1.7 | | | 8 | 3.56 | 21 | | |
| Kii Channel | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 8 | 0.16 | 99.6 | 0 | 0 |
| Grita | 4 | 42.2 | | | 4.5 | 9.3 | | | 5 | 2.7 | 17.1 | | |
| Average | 1.44 | 9.03 | 0.38 | 0.06 | 1.83 | 18.39 | 0.10 | 0.20 | 158 | 2.05 | 21.14 | 0.21 | 1.29 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Downtime (hrs/yr) | 13.0 | | 0.02 | | 34 | | 0.02 | | | 43.4 | | 0.27 | |
| FOR/U(hrs/yr) | 0.15% | | 0.0003% | | 0.38% | | 0.0002% | | | 0.49% | | 0.003% | |