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DC1020 - HVdc System Integration Study

Volume 6 - Cursory Evaluation of Alternate HVdc Configurations

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Executive Summary

Newfoundland and Labrador Hydro (Hydro) is planning to install a three-terminal HVdc system linking Labrador, Newfoundland, and New Brunswick. The proposed HVdc system will be bipolar, with each converter station having the ability to run as either rectifier or inverter. It will use both cable and overhead line, with about 40 km of cable between Labrador and Newfoundland and about 480 km between Newfoundland and New Brunswick.

The Labrador (Gull Island) converters will be nominally rated at 1600 MW; whereas, the Newfoundland (Soldiers Pond) and New Brunswick (Salisbury) stations will each be rated at 800 MW. The converters at Soldiers Pond require an overload capability of 2.0 pu for 10 minutes and 1.5 pu continuously. This would allow for the start-up of generation to avoid load shedding in the event of the loss of one pole of the HVdc system. The converters at Salisbury do not require any special overload capability and will have an overload rating which is typical of HVdc systems (10-15%).

The report "DC 1020 HVdc System Integration Study- Transient Stability Analysis" [1] presented the results of the detailed transient stability analysis of the proposed multi-terminal HVdc system. This report presents the results of a cursory evaluation of alternate HVdc configurations performed as a separate task within the overall WTO DC1020 HVdc System Integration Study. This cursory evaluation compared a number of alternative HVdc configurations considering cost, expected performance and impacts on the reliability of the overall transmission system.

The configurations considered are as follows:

a) Base case: A three-terminal HVdc link connecting Gull Island, Soldiers Pond and Salisbury. This alternative was the main focus of the system integration studies.

b) Alternative 1: A two-terminal HVdc link connecting Gull Island to Soldiers Pond and another two-terminal HVdc link connecting Soldiers Point to Salisbury.

c) Alternative 2: A two-terminal HVdc link connecting Gull Island to Soldiers Pond and another two-terminal HVdc link connecting Gull Island to Salisbury.

d) Alternative 3: A two-terminal HVdc link connecting Gull Island to Taylors Brook and another two-terminal HVdc link connecting Taylors Brook to Salisbury, in conjunction with new ac transmission from Taylors Brook to Soldiers Pond.

e) Alternative 4: A two-terminal HVdc link connecting Gull Island to Soldiers Pond and another two-terminal HVdc link connecting Taylor Brook to Salisbury, in conjunction with new ac transmission from Taylors Brook to Soldiers Pond.

f) Alternative 5: Three two-terminal HVdc links; one connecting Gull Island to Taylors Brook, one connecting Taylors Brook to Salisbury and one connecting Taylors Brook to Soldiers Pond.

The alternatives were compared in terms of the cost of the converter terminals, length of the overhead lines and cables, requirement for synchronous condensers, and advantages and disadvantages as compared to the base case multi-terminal HVdc configuration.

Converter cost calculations were made based on the assumption of 1pu$/MW for each converter of a two-terminal HVdc link. Converter costs for the base case multi-terminal HVdc configuration were increased by 10% to account additional costs associated with the multi-terminal option. The overload requirements for each alternative were determined and the corresponding converter costs calculated.

The total length of the HVdc overhead transmission line and undersea cable, along with any ac lines required for the given alternative were also determined. It should be noted that costs of the associated transmission lines and cables were not calculated; only the relative lengths were compared.

Synchronous condensers requirements on the Island of Newfoundland for the given alternative were considered based on the need to provide adequate Equivalent Short Circuit Ratio (ESCR) in the case of a single HVdc link, and the Multi-infeed Interactive Effective Short Circuit Ratio (MIESCR) in the case where two or more HVdc links terminate electrically close to one another. The MIESCR is a generalization of the ESCR index that can be used for multi-infeed systems to indicate the effect of one HVdc system on the other.

The cost of converter terminals, length of overhead lines and cables and relative amount of synchronous condensers required for the base case multi-terminal HVdc configuration and the five alternatives considered are summarized in Table 1.

Table 1
Summary of Results

Case	Converter Cost		DC OH Line		DC Cable km	ac OH Line km	Need for Synchronous Condenser
	pu$	Relative to base case	km	Relative to base case			
Base	4306	1	1488	1	520	0	Low
Alt. 1	6144	1.43	1894	1.27	520	0	High
Alt. 2	3864	0.83[1]	2170	1.46	561	0	Low
Alt. 3	6144	1.43	1082	0.73	520	800	Very High
Alt. 4	6144	1.43	1488	1	520	800	Fairly High
Alt. 5	8408	1.95	1488	1	520	0	Extremely High

[1] *No provision has been included to account for the fact that the total installed converter capacity at Gull Island is installed in two separate converter stations which should be expected to increase the cost as compared to installation of the entire capacity within a single converter.*

Salient point of the overall comparison of the alternatives includes:

- For all alternatives except alternative 2, the total cost of converters is greater than that of the base case multi-terminal HVdc configuration.
- For all alternatives except alternative 3, the total length of HVdc overhead line and cable is equal to or greater than that of the base case multi-terminal HVdc configuration. In the case of alternatives 3 and 4 an additional 800km of 230kV as transmission lines are required on the Island of Newfoundland.
- For all alternatives, synchronous condenser requirements within the Newfoundland ac system are equal to greater than those of the base case multi-terminal HVdc configuration.
- None of the alternatives considered provided any significant advantages as compared to the base case multi-terminal HVdc configurations while providing some disadvantages.

Based on the results of this cursory evaluation it is concluded that the base case multi-terminal HVdc configuration offers the lowest overall cost when considering the cost of converters, HVdc overhead lines and undersea cables, ac transmission lines, and synchronous condenser requirements. Furthermore, none of the alternatives considered offered any significant advantages over the base case multi-terminal HVdc configuration. Therefore it is recommended that none of the alternative configurations be considered as a preferable option to the base case multi-terminal HVdc configuration.

1. Introduction

Newfoundland and Labrador Hydro (Hydro) is planning to install a three-terminal HVdc system linking Labrador, Newfoundland, and New Brunswick. The proposed HVdc system will be bipolar, with each converter station having the ability to run as either rectifier or inverter. It will use both cable and overhead line, with about 40 km of cable between Labrador and Newfoundland and about 480 km between Newfoundland and New Brunswick.

The Labrador (Gull Island) converters will be nominally rated at 1600 MW; whereas, the Newfoundland (Soldiers Pond) and New Brunswick (Salisbury) stations will each be rated at 800 MW. The converters at Soldiers Pond require an overload capability of 2.0 pu for 10 minutes and 1.5 pu continuously. This would allow for the start-up of generation to avoid load shedding in the event of the loss of one pole of the HVdc system. The converters at Salisbury do not require any special overload capability and will have an overload rating which is typical of HVdc systems (10-15%).

The report "DC 1020 HVdc System Integration Study- Transient Stability Analysis" [1] presented the results of the detailed transient stability analysis of the proposed multi-terminal HVdc system. This report presents the results of a cursory evaluation of alternate HVdc configurations performed as a separate task within the overall WTO DC 1020 HVdc System Integration Study. This cursory evaluation compared a number of alternative HVdc configurations considering cost, expected performance and impacts on the reliability of the overall transmission system.

2. Evaluation of Alternate HVdc Configurations

In the following sections the budget price for a bipolar, two terminal HVdc link (two converters only, cost of transmission line is extra) is considered to be 2 per units $/MW. The cost of each converter is therefore assumed to be 1 per unit $/MW

One recent 2500MW bipolar, two terminal HVdc project has been awarded at a price of 350 million USD, which equates to a cost of 140,000 USD/MW for both converter stations or 70,000 USD/MW for each of the two converters. Based on the CIGRE report of WG 14.20 the estimated cost of one converter terminal of a 450 kV, bipolar, two terminal HVdc system is 78,750 USD/MW. Based on these values it seems that the actual cost of a converter terminal is in the range of 75,000 USD /MW to 80,000 USD/MW.

This cost can be broken down into the following items:

Table 2
Approximate Cost Breakdown for an HVdc Terminal

Engineering and Overhead	
Other Equipment	
Controls	
ac Filters	
Civil Works	
Valves	
Transformers	
Total	**100.00%**

2.1 Base Case – Multi-Terminal HVdc System

This alternative is the three-terminal HVdc system connecting Gull Island, Soldiers Pond and Salisbury as shown in Figure 1and was the main focus of the HVdc System Integration Study.

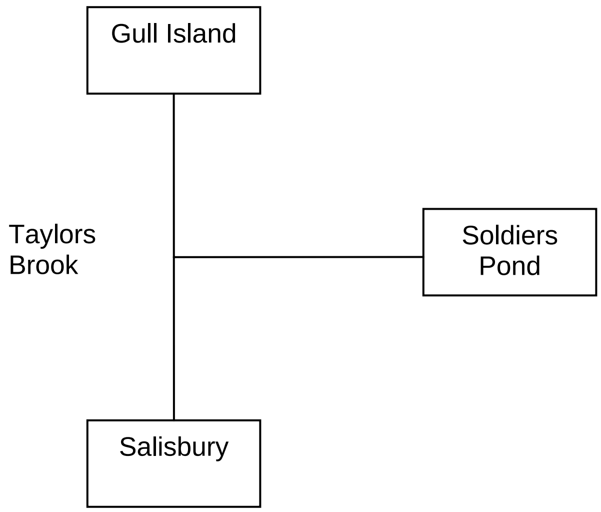

Figure 1 Base Case – Multi-Terminal HVdc System

The feasibility study has shown that this option is technically viable and is capable of delivering reliable power to Newfoundland. Based on the previous studies, the rating of the HVdc terminals are as shown in Table 3 below. The short term (10-minute) overload capacities are only needed in mono-polar operation mode.

Table 3
Converter Ratings for Base Case Three-Terminal HVdc Configuration (per Pole)

		Overload rating (MW)	
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**
Gull Island	800	1240 (1.55 pu)	1040 (1.3 pu)
Soldiers Pond	400	800 (2.0 pu)	600 (1.5 pu)
Salisbury	400	4400 (1.1 pu)	4400 (1.1 pu)
Total (per pole)	**1600**	**2480**	**2080**
Total (Bipole)	**3200**	**4960**	**4160**

2.1.1 Converter Terminal Costs

The estimated costs of each of the three terminals with this option are given in Tables 4 to 6 below. It should be mentioned that HVdc converters are generally designed with an inherent overload capability of 10%. The Gull Island and Soldiers Pond terminals in this option require larger overload capacities which will affect their costs; however the large overload capacity is required only in mono-polar operation. Upon loss of a pole, the healthy pole at Soldiers Pond must be capable of delivering the full bipolar power (800 MW) for at least 10 minutes. The healthy pole at Gull Island must be able to deliver the 800 MW required at Soldiers Pond as well as the 440 MW demanded by the healthy pole at Salisbury.

The cost of a converter station for a multi-terminal HVdc is assumed to be 10% more than a comparable converter station for a two-terminal HVdc link. This is due to the extra engineering cost and the extra equipment required for power reversal capability. Therefore in Table 4 to Table 6 the cost of converter terminals without the extra overload capacity is considered 1.1pu$/MW.

The fourth columns in Table 4 to Table 6 show the estimated effect of the large overload capacity on each item of the cost. The increased overload capacity will have minimal effect on the cost of engineering and controls and therefore these items of cost remain unchanged.

Operation in overload conditions normally requires increased capacity of the ac filters. However in this case the overload capacity is needed only when one pole is not in service. Consequently the ac filters from this pole can be used to provide the necessary reactive power support for overload operation. As a result the increased overload capacity does not affect the cost of ac filters.

HVdc thyristor valves have very short thermal time constants and therefore any increase in overload capacity of each pole (even for short term) requires similar increase in valve ratings. The cost of valves is therefore estimated to be increased in proportion to the 10-minute overload capacity. Transformers on the other hand have large thermal time constant and can handle short term overloads. Transformer MVA ratings are therefore affected only by the steady state overload capacity. Assuming that the cost of transformers is proportional to their MVA ratings, this item of cost is then increased in proportion to the steady state overload capacity of each terminal.

Increased overload capacity also affects the cost of civil work. Increased transformer, busbars, switch gear, cooling system sizes etc., means more civil work and hence higher cost. Most parts of the civil work cost increase in proportion to the steady state overload capacity. The size of ac filters and their associated civil work is not increased here; however there are items that are increased in proportion to the short term overload capacity. Therefore it seems reasonable to assume this item of cost is increased in proportion to the steady state overload capacity.

The costs of various other equipments are affected differently by the overload capacity. While certain items like Potential Transformers may remain unchanged, other items such as the ac breakers should be selected according to the short term overload capacity. On average the cost of other equipment is estimated to be increased in proportion to the steady state overload capacity.

Table 4
Estimated Cost of Gull Island Terminal for Base Case Multi-Terminal HVdc Configuration

Gull Island			
	% of total cost	**Total Cost without OL rating**	**Total Cost with OL rating**
Engineering and OH			
Other Equip			
Controls			
ac Filters			
Civil Works			
Valves			
Transformers			
Total (per pole)	**100.00%**	**1760 pu$**	**2181 pu$**

Table 5
Estimated Cost of Soldiers Pond Terminal for Base Case Multi-Terminal HVdc Configuration

Soldiers Pond			
	% of total cost	**Total Cost without OL rating**	**Total Cost with OL rating**
Engineering and OH			
Other Equip			
Controls			
ac Filters			
Civil Works			
Valves			
Transformers			
Total	**100%**	**880 pu$**	**1245 pu$**

Table 6
Estimated Cost of Salisbury Terminal for Base Case Multi-Terminal HVdc Configuration

Salisbury			
	% of total cost	**Total Cost without OL rating**	**Total Cost with OL rating**
Engineering and OH			
Other Equip			
Controls			
ac Filters			
Civil Works			
Valves			
Transformers			
Total	**100%**	**880 pu$**	**880 pu$**

The estimated total cost of the three terminals is given in Table 7 below.

Table 7
Total Estimated Converter Costs for Base Case Multi-Terminal HVdc Configuration

Location	**Estimated Cost**
Gull Island	2181 pu$
Soldiers Pond	1245 pu$
Salisbury	880 pu$
Total	**4306 pu$**

2.1.2 Transmission Lines and Cables

The required overhead transmission lines and cables for this option are summarized in Table 8. Note that in the discussion of cable lengths no consideration is given to the need for multiple cables in parallel to support the required dc current. The lengths given correspond only to the estimated length of cable and do not consider the need for cables in parallel.

Table 8
Overhead Line and Cable Lengths for Base Case Multi-Terminal HVdc Configuration

Section	OHL (km)	Cable (km)
Gull Island to Strait of Belle Isles	407	
Across Strait of Belle Isles		40.7 (two poles)
Strait of Belle Isle to Taylors Brook	275	
Taylors Brook to Soldiers Pond	406	
Taylors Brook to Cape Ray	300	
Across Cabot Strait		480 (two poles)
Coast of New Brunswick to Salisbury	100	
Total	**1488**	**520.7**

2.1.3 Effective Short Circuit Ratio

Effective short circuit ratio (ESCR) is defined as follows:

ESCR = (Short circuit MVA at AC bus – MVA rating of filters)/Rated DC power

Based on industry experience it can be stated that low or very low SCR in itself is not a technical limitation in the evaluation of an HVdc transmission option, but it must be recognized that decreasing short circuit ratio (and therefore the ESCR) results in overall decreased performance of the interconnected ac/dc systems. The effects of reducing ESCR on overall performance becomes even more pronounced for HVdc system which utilize long cables.

Based on the system data provided for the Power Flow and Transient Stability study portions of WTO DC 1020 and results of the Transient Stability study [1] which found that one 300MVAr synchronous condenser must be in-service at both the Pipers Hole and Soldiers Pond 230kV ac buses, the Effective Short Circuit Ratios (ESCRs) at the three terminals are as follows:

Gull Island ESCR = 4.81
Soldiers Pond ESCR = 3.12
Salisbury ESCR =

The results of the transient Stability Study [1] have shown good performance of the multi-terminal HVdc system and indicate that the ESCRs at each of the three terminals are sufficient.

It should be noted that the Transient Stability Study [1] found the need for having one 300MVAr synchronous condenser in service at Pipers Hole and Soldiers Pond was based on increasing the ESCR and providing system inertia.

2.2 Alternative 1 – Two Two-Terminal HVdc Links – Option 1

This alternative includes two separate Two-terminal HVdc systems, one connecting Gull Island to Soldiers Pond and another connecting Soldiers Point to Salisbury as shown in Figure 2.

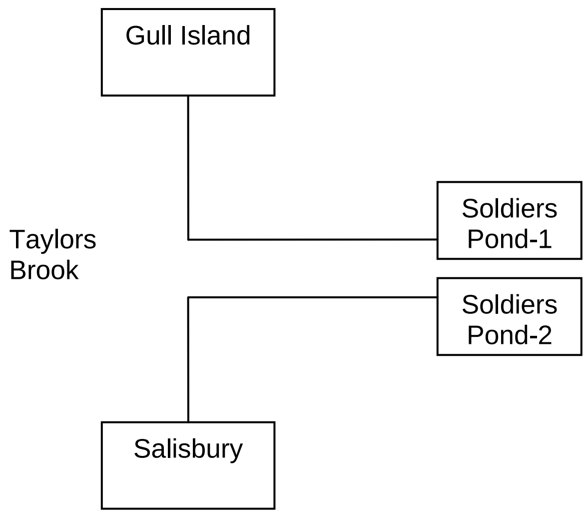

Figure 2 Alternative 1 - Two Two-Terminal HVdc Systems - Option 1

Nominal and overload ratings of the required terminals for this alternative are as shown in Table 9.

Table 9
Nominal and Overload Ratings for Alternative 1 (per Pole)

		Overload rating (MW)	
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**
Gull Island	800	1600 (2.0 pu)	1200 (1.5 pu)
Soldiers Pond 1	800	1600 (2.0 pu)	1200 (1.5 pu)
Soldiers Pond 2	400	440 (1.1 pu)	440 (1.1 pu)
Salisbury	400	440 (1.1 pu)	440 (1.1 pu)
Total (per pole)	**2400**	**4080**	**3280**
Total (Bipole)	**4800**	**8160**	**6560**

In this alternative, under the worst case scenario where 1600MW flows from Gull Island to Soldiers Pond 1 and 800 MW flows from Soldiers Pond 2 to Salisbury; if one pole in the Gull Island to Soldiers Pond 1 system trips the healthy pole must be able to transmit the whole 1600MW to maintain the net power delivered to the Newfoundland system at 800MW and also maintain the 800MW power flow in the Soldiers Pond 2 to Salisbury HVdc system. Therefore in this alternative, the Gull Island and Soldiers Pond 1 terminals must have 100% short term and 50% steady state overload capacities. The Soldiers Pond 2 to Salisbury HVdc link however does not need an increased overload capacity. In case of a pole loss in Soldiers Pond 2 to Salisbury link the New Brunswick system should be able to absorb the power shortage.

When comparing to the base case multi-terminal configuration, alternative 1 requires a total installed converter capacity with 1.5 times the nominal rating, 1.65 times the 10-minute overload rating, and 1.58 times the steady state overload rating.

2.2.1 Converter Terminal Costs

Repeating the analysis of Table 5 to Table 7, cost estimates for the converter terminals for alternative 1 are given in Table 10.

Table 10
Estimated cost of converter terminals for Alternative 1

Location	Nominal rating (MW)	10 Min. OL (MW)	Steady State OL (MW)	Cost
Gull Island (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1(pu$/MW) x 800(MW) x 1.42 = 1136 pu$
Soldiers Pond 1 (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1(pu$/MW) x 800(MW) x 1.42 = 1136 pu$
Soldiers Pond 2 (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	1(pu$/MW) x 400(MW) = 400 pu$
Salisbury (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	1(pu$/MW) x 400(MW) = 400 pu$
Total (per Pole)	**2400**	**4080**	**3280**	**3072 pu$**
Total (Bipole)	**4800**	**8160**	**6560**	**6144 pu$**

Due to the increased overload capacity, it is seen that the cost of the Gull Island and Soldiers Pond 1 terminals has increased by approximately 43% as compared to the base case multi-terminal HVdc configuration. The cost of the Salisbury terminal has been reduced by 10% due to the fact that this is now a two terminal (not a multi-terminal) converter; however a new Soldiers Pond 2 converter with a rating equal to that of the Salisbury converter is required.

When comparing the converter costs for alternative 1 to the base case multi-terminal HVdc configuration it is seen that the overall converter costs have increased by approximately 43%.

2.2.2 *Transmission Lines and Cables*

The approximate lengths of the overhead lines and cables required in this alternative are given in Table 11.

Table 11
Approximate length of the required OH lines and cables for Alternative-1

Section	OHL (km)	Cable (km)
Gull Island to Strait of Belle Isle	407	
Across Strait of Belle Isles		40.7 (two poles)
Strait of Belle Isle to Taylors Brook	275	
Taylors Brook to Soldiers Pond 1	406	
Bipole 1 Subtotal	**1088**	**40.7**
Soldiers Pond 2 to Taylors Brook	406	
Taylors Brook to Cape Ray	300	
Across Cabot Strait		480 (two poles)
Coast of New Brunswick to Salisbury	100	
Bipole 2 Subtotal	**806**	**480**
Total	**1894**	**520.7**

Here it is assumed that the transmission line from Gull Island to Soldiers Pond follows the same route as the base case multi-terminal HVdc system. It is also assumed that a second overhead line is built between Soldiers Pond and Taylors Brook which is then extended to Cape Ray on the same route as the base case multi-terminal HVdc system. The submarine cable and the overhead line within New Brunswick are identical to the multi-terminal option.

Comparing the lengths of overhead lines and cables required for Alternative 1 to those required in the Base Case it is seen that Alternative 1 requires 27% more overhead line and the same length of undersea cable as the base case.

2.2.3 *Effective Short Circuit Ratio*

The effective short circuit ratios at Gull Island and Salisbury in this option are identical to those of the base case multi-terminal configuration.

At Soldiers Pond there are two HVdc terminals in this case, making a multi-infeed system. Because of the interactions between the two nearby HVdc terminals the conventional definition of the ESCR cannot be used in a multi-infeed system. The Multi-infeed Interactive Effective Short Circuit Ratio (MIESCR) is a generalization of the ESCR index that can be used for multi-infeed systems to indicate the effect of one HVdc system on the other.

For converter 'i' the MIESCR index is defined as:

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

Where:

- SCCi is the short circuit MVA available at the converter bus
- Qfi is the bus filter and capacitor MVA of the converter 'i'
- Pdci is the rated dc power of the converter 'i'
- Pdcj is the rated dc power of the adjacent converter 'j'
- MIIFj,I is the Multi Infeed Interaction Factor between converters j and i.

MIIF is an index describing the proximity of the converters that varies between one for converters connected to the same ac bus, and zero for converters infinitely far apart.

At Soldiers Pond the two converters will be electrically close and therefore the MIFF will be close to one. Assuming the Newfoundland ac system is identical to that used in the base case multi-terminal configuration the MIESCR index for the two converters (Soldiers Pond 1 and 2) can be calculated as:

Soldiers Pond 1 (1600 MW Converter) MIESCR = 0.833

Soldiers Pond 2 (800 MW Converter) MIIESCR = 1.039

The MIISCR for both converters is very low, indicating that more synchronous condensers would need to be installed at Soldiers Pond to increase the system short circuit capacity.

When comparing to the base case multi-terminal HVdc configuration it is concluded that additional synchronous condensers would be required in the Newfoundland system to support the HVdc transmission proposed in Alternative 1.

2.2.4 Advantages

The following is a list of advantages of this alternative as compared to the base case multi-terminal configuration:

- The two HVdc links could be built in stages, with the Gull Island to Soldiers Pond 1 link built prior to the Soldiers Pond 2 to Salisbury link. However, it is most likely that the Gull Island to Soldiers Pond 1 HVdc link would have to be built initially to its final capacity since staging of this two terminal link would not present substantial economic benefits.

- Only conventional two-terminal HVdc links are used therefore some of the challenges associated with the multi-terminal option are avoided. HVdc controls are less complicated compared to the base case multi-terminal HVdc system.
- The effect of the long dc cable is removed from the circuit between Gull Island and Soldiers Pond and its performance will improve.
- If the Soldiers Pond 1 converters are unavailable then power can still be supplied to the Newfoundland system by operating Salisbury as a rectifier and Soldiers Pond 2 as an inverter.
- There is the potential for sharing of spare transformers between the Soldiers Pond 1 and 2 converters depending on the design, physical locations, and configurations of the transformers in the two converter stations.

2.2.5 Disadvantages

The following is a list of disadvantages of this alternative as compared to the base case multi-terminal configuration:

- This alternative requires 1600 MW more of installed converters, adding more than 2000pu$ (49%) to the converter station costs.
- This alternative requires approximately 406km (27%) more overhead line.
- The two separate HVdc links which terminate electrically close to one another at Soldiers Pond would results in a multi-infeed HVdc scenario. Although the two HVdc links are effectively independent of one another, the performance of one will greatly impact the performance of the other due to the close coupling at Soldiers Pond.
- The Multi-Infeed ESCR (MIESCR) in Newfoundland is very low, requiring to the need to install more synchronous condensers.
- Potential for increased overvoltages at Soldiers Pond due to increased ac filter requirements.
- Increased operating losses due to the additional filters and need to convert 800MW from dc to ac and again from ac to dc in Soldiers Pond.
- Increased maintenance due to the fact that there are now two converter stations at Soldiers Pond.
- Increased size and complexity of the overall converter station at Soldiers Pond.
- Potential for increased spares requirements due to different equipment ratings within the Soldiers Pond 1 and 2 converter stations.

2.2.6 Summary

Based on the results of this cursory evaluation it is seen that when compared to the base case multi-terminal HVdc configuration the alternative of two HVdc links, one from Gull Island to Soldiers Pond 1 and the second from Soldiers Pond 2 to Salisbury will result in:

- increased converter costs;
- increased HVdc overhead line lengths;
- additional synchronous condensers within the Newfoundland system and their associated costs.

In addition the alternative does not provide any substantial technical advantages over the base case multi-terminal HVdc while having some technical disadvantages.

It is therefore concluded that the alternative of providing two two-terminal HVdc systems, one from Gull Island to Soldiers Pond 1 and the second from Soldiers Pond 2 to Salisbury is not recommended above the base case multi-terminal HVdc configuration.

2.3 Alternative 2 – Two Two-Terminal HVdc Links – Option 2

This alternative includes two, two-terminal HVdc systems, one connecting Gull Island to Soldiers Pond and another connecting Gull Island to Salisbury as shown in Figure 3.

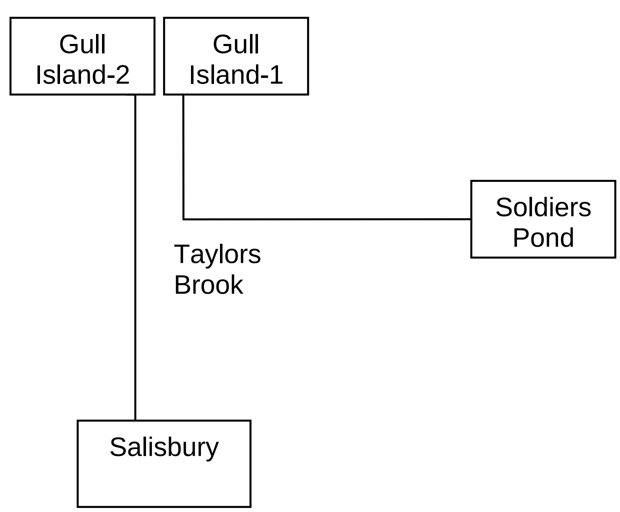

Figure 3 Two Two-Terminal HVdc Links- Option 2 (Alternative-2)

Nominal and overload ratings of the required terminals for this alternative are as shown in Table 12 below.

Table 12
Nominal and Overload Ratings for Alternative 2 (per pole)

		Overload rating (MW)	
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**
Gull Island 1	400	800 (2.0 pu)	600 (1.5 pu)
Gull Island 2	400	440 (1.1 pu)	440 (1.1 pu)
Soldiers Pond	400	800 (2.0 pu)	600 (1.5 pu)
Salisbury	400	440 (1.1 pu)	440 (1.1 pu)
Total (per pole)	**1600**	**2480**	**2080**
Total (per pole)	**3200**	**4960**	**4160**

In this alternative the first two terminal HVdc link connecting Gull Island 1 and Soldiers Pond must have 100% overload capacity for at least 10 minutes. This is required to avoid a power shortage in Newfoundland in the case of the loss of a pole. The second HVdc link between Gull Island 2 and Salisbury does not require an increased overload capacity.

When comparing to the base case multi-terminal configuration, alternative 2 requires installed converter capacity with the same nominal rating, 10-minute overload rating, and steady state overload rating.

2.3.1 Converter Terminal Costs

Repeating the analysis of Table 5 to Table 7, cost estimates for the converter terminals for alternative 2 are given in Table 13.

Table 13
Estimated Cost of Converter Terminals for Alternative 2

		Overload rating (MW)		
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**	**Estimated Cost**
Gull Island 1 (per pole)	400	800 (2.0 pu)	600 (1.5 pu)	566 pu$
Gull Island 2 (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	400 pu$
Soldiers Pond (per pole)	400	800 (2.0 pu)	600 (1.5 pu)	566 pu$
Salisbury (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	400 pu$
Total (per pole)	**1600**	**2480**	**2080**	**1932 pu$**
Total (per pole)	**3200**	**4960**	**4160**	**3864 pu$**

Following the same approach taken for the base case, effect of the increased overload capacity on the cost of the Gull Island 1 and Soldiers Pond terminals can be calculated. Gull Island 2 and Salisbury terminals are standard two-terminal converters and their costs are strictly 1pu$/MW.

In this alternative it is seen that the combined installed converter capacity is the same as that for the base case multi-terminal configuration, however two-terminal HVdc links are used, therefore given the analysis used, the cost is reduced. It should be noted that in the analysis used there is no cost adjustment to reflect the fact that the total installed converter capacity at Gull Island for alternative 2 is located within two separate converter stations as compared to the base case multi-terminal configuration which requires only a single converter station at Gull Island.

2.3.2 Transmission Lines and Cables

The approximate lengths of the overhead lines and cables required in this alternative are given in Table 14.

Table 14
Approximate length of OH lines and cables for Alternative-2

Section	OHL (km)	Cable (km)
Gull Island 1 to Strait of Belle Isle	407	
Across Strait of Belle Isle		40.7 (two poles)
Strait of Belle Isle to Taylors Brook	270	
Taylors Brook to Soldiers Pond	406	
Bipole 1 Subtotal	**1088**	**40.7**
Gull Island 2 to Strait of Belle Isle	407	
Across Strait of Belle Isle		40.7 (two poles)
Strait of Belle Isle to Taylors Brook	270	
Taylors Brook to Cape Ray	300	
Across Cabot Strait		480 (two poles)
Coast of New Brunswick to Salisbury	100	
Bipole 2 Subtotal	**1082**	**520.7**
Total	**2170**	**561.4**

In this alternative two independent transmission lines connect Gull Island to Soldiers Pond and Gull Island to Salisbury. The first line from Gull Island 1 to Soldiers Pond is assumed to follow the same route as the base case multi-terminal configuration and include a total of 1088km of overhead line and 40.7km of submarine cable. The second line from Gull Island 2 to Salisbury is also assumed to follow the same route as base case multi-terminal configuration and include a total of 2170km of overhead line and 520.7km of cable.

Comparing the lengths of overhead lines and cables required for Alternative 2 to those required in the Base Case it is seen that Alternative 2 requires 46% more overhead line and 8% more undersea cable as the base case.

2.3.3 *Effective Short Circuit Ratio*

In this alternative there are two HVdc terminals at Gull Island. The MIESCR for these terminals are shown below and are seen to be reasonably high.

Gull Island 1 MIESCR = 5.12

Gull Island 2 MIESCR = 5.12

The effective short circuit ratios for the Soldiers Pond and Salisbury terminals are unchanged from the base case multi-terminal HVdc configuration.

When comparing to the base case multi-terminal HVdc configuration it is seen that no additional synchronous condensers would be required.

2.3.4 Advantages

The following is a list of advantages of this alternative as compared to the base case multi-terminal configuration:

- The analysis indicates a potential reduction in the converter costs of approximately 10%. It should be noted that the analysis does not account for the fact that the total converter capacity at Gull Island would now be split between two converters in separate HVdc links which would tend to increase the cost as compared to installing the same capacity within a single converter.
- The two HVdc links could be built in stages, with the Gull Island 1 to Soldiers Pond link built prior to the Gull Island 2 to Salisbury link. It is most likely that the transmission lines and cables across the Strait of Belle Isle for both HVdc links would be installed at the same time due to construction costs. Staggering construction of the converter stations at Gull Island would also incur some additional costs.
- The two DC links are more independent, therefore power delivery to the Newfoundland system is more reliable and less affected by the events in New Brunswick system and the Gull Island 2 to Salisbury HVdc link.
- Only conventional two-terminal HVdc links are used therefore some of the challenges associated with the multi-terminal option are avoided. HVdc controls are less complicated compared to the base case multi-terminal HVdc system.
- The effect of the long dc cable is removed from the circuit between Gull Island 1 and Soldiers Pond and its performance.

If one converter is unavailable at Gull Island, there is no impact on the converters of the other HVdc link.

2.3.5 Disadvantages

- This alternative requires approximately 680km (46%) more overhead line and 40km (8%) more undersea cable.
- Loss of transmission capacity from Labrador to Soldiers Pond cannot be offset by importing power from New Brunswick to Newfoundland.
- Direct import of power from New Brunswick to Newfoundland and vice versa is not possible. Importing power from New Brunswick to Newfoundland via Labrador would result in increased losses.
- Increased maintenance due to the fact that there are now two converter stations at Gull Island.
- Increased size and complexity of the overall converter station at Gull Island.
- Potential for increased spares requirements due to different equipment ratings within the Gull Island 1 and 2 converter stations.

2.3.6 Summary

Based on the results of this cursory evaluation it is seen that when compared to the base case multi-terminal HVdc configuration the alternative of two HVdc links, one from Gull Island 1 to Soldiers Pond and the second from Gull Island 2 to Salisbury will result in:

- decrease in converter costs (potentially); and
- greatly increased HVdc overhead line and cable lengths.

In addition the alternative does not provide any substantial technical advantages over the base case multi-terminal HVdc while having some technical disadvantages.

It is therefore concluded that the alternative of providing two, two-terminal HVdc systems, one from Gull Island 1 to Soldiers Pond and the second from Gull Island 2 to Salisbury is not recommended above the base case multi-terminal HVdc configuration.

2.4 Alternative 3 – Two Two-Terminal HVdc Links and ac – Option 1

This alternative includes two, two-terminal HVdc systems, one connecting Gull Island to Taylors Brook and the other connecting Taylors Brook to Salisbury plus the addition of ac transmission connecting Taylors Brook to Soldiers Pond. New ac transmission between Taylors Brook and Soldiers Pond is assumed to be required as the existing east-west lines in Newfoundland are heavily loaded.

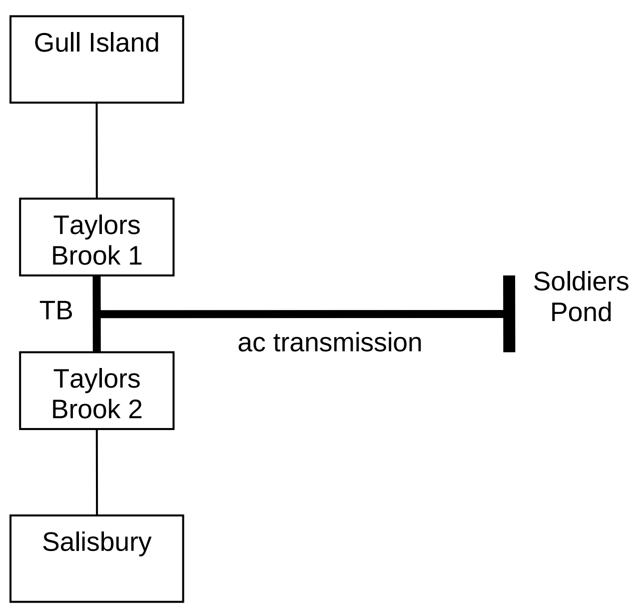

Figure 4 Two Two-Terminal HVdc Links and ac – Option 1 (Alternative 3)

Nominal and overload ratings of the required terminals for this alternative are as shown in Table 15.

Table 15
Nominal and Overload Ratings for Alternative 3 (per pole)

		Overload rating (MW)	
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**
Gull Island	800	1600 (2.0 pu)	1200 (1.5 pu)
Taylors Brook 1	800	1600 (2.0 pu)	1200 (1.5 pu)
Taylors Brook 2	400	440 (1.1 pu)	440 (1.1 pu)
Salisbury	400	440 (1.1 pu)	440 (1.1 pu)
Total (per pole)	**2400**	**4080**	**3280**
Total (Bipole)	**4800**	**8160**	**6560**

These requirements are exactly the same as alternative 1. Similar to that case, if one pole in Gull Island to Taylors Brook 1 system trips the healthy pole must be able to transmit the full power to maintain the net power delivered to the Newfoundland system at 800MW. The power flow in Taylors Brook 2 to Salisbury system should not be affected by this event. The Taylors Brook 2 to Salisbury link however does not need an increased overload capacity; in the case of loss of a pole in the Taylors Brook 2 to Salisbury link the New Brunswick system should be able to absorb the power shortage.

When comparing to the base case multi-terminal configuration, alternative 3 requires a total installed converter capacity with 1.5 times the nominal rating, 1.65 times the 10-minute overload rating, and 1.58 times the steady state overload rating.

2.4.1 Converter Terminal Costs

Repeating the analysis of Table 5 to Table 7, cost estimates for the converter terminals for alternative 3 are given in Table 16.

Table 16
Converter terminal cost estimate for Alternative-3

Location	Nominal rating (MW)	10 Min. OL (MW)	Steady State OL (MW)	Cost
Gull Island (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1136 pu$
Taylors Brook 1 (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1136 pu$
Taylors Brook 2 (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	400 pu$
Salisbury (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	400 pu$
Total (per pole)	**2400**	**4080**	**3280**	**3072 pu$**
Total (Bipole)	**4800**	**8160**	**6560**	**6144 pu$**

Due to the increased overload capacity, it is seen that the cost of the Gull Island terminal has increased by approximately 5% as compared to the base case multi-terminal HVdc configuration. The cost of the two terminals at Taylors Brook combined is approximately 2.47 times the cost of the Soldiers Pond converter in the base case multi-terminal HVdc configuration. The cost of the Salisbury terminal has been reduced by 10% due to the fact that this is now a two terminal (not a multi-terminal) converter.

When comparing the converter costs for alternative 3 to the base case multi-terminal HVdc configuration it is seen that the overall converter costs have increased by approximately 43%. (Note that costs of the new ac transmission required to connect Taylors Brook to Soldiers Pond has not been factored into the above converter costs.)

2.4.2 Transmission Lines and Cables

The approximate lengths of the overhead lines and cables required in this alternative are given in Table 17.

Table 17
Approximate length of the required OH lines and cables for Alternative-3

Section	OHL (km)	Cable (km)	ac OHL (km)
Gull Island to Strait of Belle Isle	407		
Across Strait of Belle Isle		40.7 (two poles)	
Strait of Belle Isle to Taylors Brook	275		
Bipole1 Subtotal	**682**	**40.7**	
Taylors Brook to Cape Ray	300		
Across Cabot Strait		480 (two poles)	
Coast of New Brunswick to Salisbury	100		
Bipole2 Subtotal	**400**	**480**	
Taylors Brook to Soldiers Pond			**2 x 400**
Total	**1082**	**520.7**	**800**

Here it is assumed that the HVdc transmission line and cable from Gull Island to Taylors Brook follows the same route as the base case multi-terminal HVdc system. It is also assumed that the second HVdc line and cable between Taylors Brook and Salisbury follows the same route as the base case multi-terminal HVdc system. In addition to the HVdc lines, the combined length of the ac transmission required to interconnect Taylors Brook and Soldiers Pond is included. It is assumed that at least two 230kV lines would be required and the route would be the same as that for the HVdc line in the original multi-terminal configuration between Taylors Brook and Soldiers Pond.

Comparing the lengths of overhead lines and cables required for Alternative 3 to those required in the Base Case it is seen that Alternative 3 requires 27% less overhead line and the same undersea cable as the base case; however alternative 3 also requires 800km of 230kV ac transmission lines on the Island of Newfoundland.

2.4.3 Effective Short Circuit Ratio

The effective short circuit ratios at Gull Island and Salisbury in this option are identical to the three-terminal option.

At Taylors Brook however there are two HVdc systems terminating next to each other and hence MIESCR must be calculated for both converters. The Short Circuit Capacity at this bus depends on the parameters of the planed ac line(s) as well as its terminating bus. Due to the weakness of the existing system at this area it is anticipated that MIESCR at Taylors Brook will be very low (particularly for the 1600MW converter). As a result large amount of synchronous condensers will be required to raise MIESCR to an acceptable level.

When comparing to the base case multi-terminal HVdc configuration it is concluded that a large number of additional synchronous condensers would be required in the Newfoundland system to support the HVdc transmission at Taylors Brook proposed in Alternative 3.

2.4.4 Advantages

The following is a list of advantages of this alternative as compared to the base case multi-terminal configuration:

- The total length of HVdc overhead line is reduced.
- The two HVdc links could be built in stages, with the Gull Island to Taylors Brook 1 link built prior to the Taylors Brook 2 to Salisbury link. However, it is most likely that the Gull Island to Taylors Brook 1 HVdc link would have to be built initially to its final capacity since staging of this two terminal link would not present substantial economic benefits.
- Only conventional two-terminal HVdc links are used therefore some of the challenges associated with the multi-terminal option are avoided. HVdc controls are less complicated compared to the base case multi-terminal HVdc system.
- The effect of the long dc cable is removed from the circuit between Gull Island and Taylors Brook and its performance.
- If the Gull Island to Taylors Brook 1 link is unavailable then power can still be supplied to the Newfoundland system by operating Salisbury as a rectifier and Taylors Brook 2 as an inverter.

This option has all advantages of alternative-1, however compared to that case the total length of DC transmission lines is reduced here. Transmission line losses are also expected to be reduced as the maximum power transfer between TB and SP is now 800MW, while in alternative-1 BiPole1 and 2 in total transfer 1800MW on this part of the route.

2.4.5 Disadvantages

The following is a list of disadvantages of this alternative as compared to the base case multi-terminal configuration:

- This alternative requires 1600 MW more of installed converters, adding more than 2000 pu$ (49%) to the converter station costs.
- This alternative requires new ac transmission lines to interconnect Taylors Brook to Soldiers Pond. It is anticipated that at least two 230kV lines will be required with a total installed length of approximately 800 km.
- The two separate HVdc links which terminate at Taylors Brook would results in a multi-infeed HVdc scenario. Although the two HVdc links are effectively independent of one another, the performance of one will greatly impact the performance of the other due to the close coupling at Taylors Brook.
- The Multi-Infeed ESCR (MIESCR) in Newfoundland is very low, requiring to the need to install a large number of synchronous condensers.

- A large sub-station would have to be established at Taylors Brook.
- Potential for increased overvoltages at Taylors Brook due to increased ac filter requirements.
- Increased operating losses due to the additional filters and need to convert 800 MW from dc to ac and again from ac to dc at Taylors Brook.
- Increased maintenance due to the fact that there are now two converter stations at Taylors Brook.
- Potential for increased spares requirements due to different equipment ratings within the Taylors Brook 1 and 2 converter stations.

2.4.6 Summary

Based on the results of this cursory evaluation it is seen that when compared to the base case multi-terminal HVdc configuration the alternative of two HVdc links, one from Gull Island to Taylors Brook 1 and the second from Taylors Brook 2 to Salisbury, in conjunction with new ac transmission interconnecting Taylors Brook to Soldiers Pond will result in:

- increased converter costs;
- reduced HVdc overhead line lengths;
- new ac transmission line requirements within the Newfoundland system; and
- large number of additional synchronous condensers within the Newfoundland system and their associated costs.

In addition the alternative does not provide any substantial technical advantages over the base case multi-terminal HVdc while having some technical disadvantages.

It is therefore concluded that the alternative of providing two, two-terminal HVdc systems, one from Gull Island to Taylors Brook 1 and the second from Taylors Brook 2 to Salisbury combined with new ac transmission facilities to interconnect Taylors Brook to Solders Pond is not recommended above the base case multi-terminal HVdc configuration.

2.5 Alternative 4 – Two Two-Terminal HVdc Links and ac – Option 2

This alternative includes two, two-terminal HVdc systems, one connecting Gull Island to Soldiers Pond and the other connecting Taylors Brook to Salisbury plus the addition of ac transmission connecting Taylors Brook to Soldiers Pond. New ac transmission between Taylors Brook and Soldiers Pond is assumed to be required as the existing east-west lines in Newfoundland are heavily loaded. The basic configuration is shown in Figure 5.

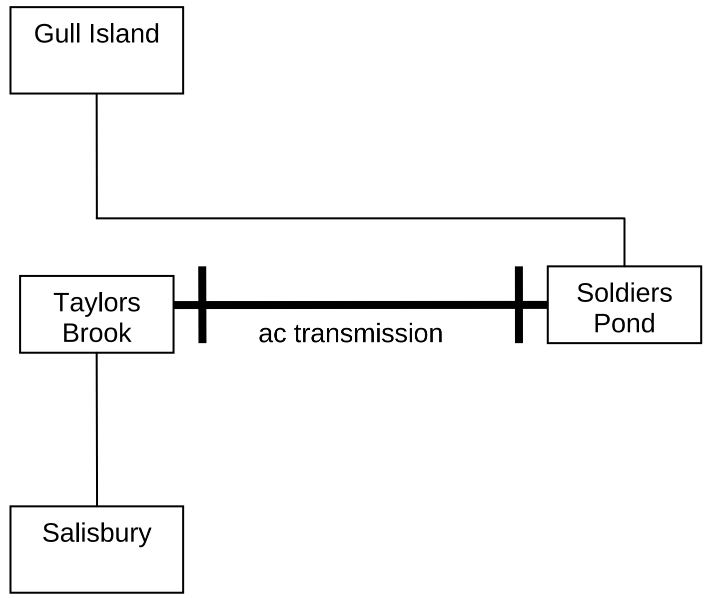

Figure 5 Two Two-Terminal HVdc Links and ac – Option 2 (Alternative-4)

Nominal and overload ratings of the required terminals for this alternative are as shown in Table 18.

Table 18
Nominal and Overload Ratings for Alternative 4 (per pole)

		Overload rating (MW)	
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**
Gull Island	800	1600 (2.0 pu)	1200 (1.5 pu)
Soldiers Pond	800	1600 (2.0 pu)	1200 (1.5 pu)
Taylors Brook	400	440 (1.1 pu)	440 (1.1 pu)
Salisbury	400	440 (1.1 pu)	440 (1.1 pu)
Total (per pole)	**2400**	**4080**	**3280**
Total (Bipole)	**4800**	**8160**	**6560**

These requirements are exactly the same as alternative 1. Similar to that case, if one pole in Gull Island to Soldiers Pond system trips the healthy pole must be able to transmit the full power to maintain the net power delivered to the Newfoundland system at 800MW. The power flow in Taylors Brook to Salisbury system should not be affected by this event. The Taylors Brook to Salisbury link however does not need an increased overload capacity; in the case of loss of a pole in the Taylors Brook to Salisbury link the New Brunswick system should be able to absorb the power shortage.

When comparing to the base case multi-terminal configuration, alternative 4 requires a total installed converter capacity with 1.5 times the nominal rating, 1.65 times the 10-minute overload rating, and 1.58 times the steady state overload rating.

2.5.1 *Converter Terminal Costs*

Repeating the analysis of Table 5 to Table 7, cost estimates for the converter terminals for alternative 4 are given in Table 19.

Table 19
Converter terminal cost estimate for Alternative 4

Location	Nominal rating (MW)	10 Min. OL (MW)	Steady State OL (MW)	Cost
Gull Island (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1136 pu$
Soldiers Pond (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1136 pu$
Taylors Brook (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	400 pu$
Salisbury (per pole)	400	440 (1.1 pu)	440 (1.1 pu)	400 pu$
Total (per pole)	**2400**	**4080**	**3280**	**3072 pu$**
Total (per pole)	**4800**	**8160**	**6560**	**6144 pu$**

Due to the increased overload capacity, it is seen that the cost of the Gull Island terminal has increased by approximately 5% as compared to the base case multi-terminal HVdc configuration. The combined cost of the two terminals at Soldiers Pond and Taylors Brook is approximately 2.47 times the cost of the Soldiers Pond converter in the base case multi-terminal HVdc configuration. The cost of the Salisbury terminal has been reduced by 10% due to the fact that this is now a two terminal (not a multi-terminal) converter.

When comparing the converter costs for alternative 4 to the base case multi-terminal HVdc configuration it is seen that the overall converter costs have increased by approximately 43%. (Note that costs of the new ac transmission required to connect Taylors Brook to Soldiers Pond has not been factored into the above converter costs.)

2.5.2 *Transmission Lines and Cables*

The approximate lengths of the required overhead lines and cables in this case are given in Table 20.

Table 20
Approximate length of the required OH lines and cables for Alternative-4

Section	OHL (km)	Cable (km)	ac OHL (km)
Gull Island to Strait of Belle Isle	407		
Across Strait of Belle Isle		40.7 (two poles)	
Strait of Belle Isles to Taylors Brook	275		
Taylors Brook to Soldiers Pond	406		
Bipole1 Subtotal	**1088**	**40.7**	
Taylors Brook to Cape Ray	300		
Across Cabot Strait		480 (two poles)	
Coat of New Brunswick to Salisbury	100		
Bipole2 Subtotal	**400**	**480**	
Taylors Brook to Soldiers Pond			**2 x 400**
Total	**1488**	**520.7**	**800**

Here it is assumed that the HVdc transmission line and cable from Gull Island to Soldiers Pond follows the same route as the base case multi-terminal HVdc system. It is also assumed that the second HVdc line and cable between Taylors Brook and Salisbury follows the same route as the base case multi-terminal HVdc system. In addition to the HVdc lines, the combined length of the ac transmission required to interconnect Taylors Brook and Soldiers Pond is included. It is assumed that at least two 230kV lines would be required and the route would be the same as that for the HVdc line between Taylors Brook and Soldiers Pond.

Comparing the lengths of overhead lines and cables required for Alternative 4 to those required in the Base Case it is seen that Alternative 4 requires the same length of HVdc overhead line and the same undersea cable as the base case; however alternative 4 also requires 800km of 230kV ac transmission lines on the Island of Newfoundland.

2.5.3 *Effective Short Circuit Ratio*

The effective short circuit ratios at Gull Island and Salisbury in this option are identical to the three-terminal option.

With the new ac lines connecting Taylors Brook and Soldiers Pond, the two HVdc terminals at these buses will electrically become close to each other and hence MIESCR must be calculated for both converters. The Multi Infeed Interaction Factor between the two terminals depends on the parameters of the new ac lines and cannot be estimated at this point. However, large amount of synchronous condensers are expected to be required at Taylors Brook to achieve reasonably high MIESCR. Compared to the three-terminal case, MIESCR at Soldiers Pond will be much lower. This is because of the larger rating of the converter (1600MW vs. 800MW) and also the proximity of the Taylors Brook terminal. As a result more synchronous condensers are likely to be required at this bus as well.

When comparing to the base case multi-terminal HVdc configuration it is concluded that a large number of additional synchronous condensers would be required in the Newfoundland system to support the HVdc transmission at Soldiers Pond and Taylors Brook proposed in Alternative 4.

2.5.4 Advantages

The following is a list of advantages of this alternative as compared to the base case multi-terminal configuration:

- The total length of HVdc overhead line is reduced.
- The two HVdc links could be built in stages, with the Gull Island to Soldiers Pond link built prior to the Taylors Brook to Salisbury link. However, it is most likely that the Gull Island to Soldiers Pond HVdc link would have to be built initially to its final capacity since staging of this two terminal link would not present substantial economic benefits.
- Only conventional two-terminal HVdc links are used therefore some of the challenges associated with the multi-terminal option are avoided. HVdc controls are less complicated compared to the base case multi-terminal HVdc system.
- The effect of the long dc cable is removed from the circuit between Gull Island and Soldiers Pond and its performance.
- If the Gull Island to Soldiers Pond link is unavailable then power can still be supplied to the Newfoundland system by operating Salisbury as a rectifier and Taylors Brook as an inverter.

2.5.5 Disadvantages

The following is a list of disadvantages of this alternative as compared to the base case multi-terminal configuration:

- This alternative requires 1600 MW more of installed converters, adding close to 2000pu$ (43%) to the converter station costs.
- This alternative requires new ac transmission lines to interconnect Taylors Brook to Soldiers Pond. It is anticipated that at least two 230kV lines will be required with a total installed length of approximately 800 km.
- The two separate HVdc links which terminate at Soldiers Pond and Taylors Brook would results in a multi-infeed HVdc scenario. Although the two HVdc links are effectively independent of one another, the performance of one will greatly impact the performance of the other.
- The Multi-Infeed ESCR (MIESCR) in Newfoundland is very low, requiring to the need to install a large number of synchronous condensers.
- A large sub-station would have to be established at Taylors Brook.
- Increased operating losses due to the additional filters and need to convert 800MW from dc to ac and again from ac to dc at Soldiers Pond.

- Increased maintenance due to the fact that there are now two converter stations on the island, one at Solders Pond and one at Taylors Brook.
- Increased spares requirements due to the physical separation of the Soldiers Pond and Taylors Brook converter stations.

2.5.6 Summary

Based on the results of this cursory evaluation it is seen that when compared to the base case multi-terminal HVdc configuration the alternative of two HVdc links, one from Gull Island to Soldiers Pond and the second from Taylors Brook 2 to Salisbury, in conjunction with new ac transmission interconnecting Taylors Brook to Soldiers Pond will result in:

- increased converter costs;
- reduced HVdc overhead line lengths;
- new ac transmission line requirements within the Newfoundland system; and
- large number of additional synchronous condensers within the Newfoundland system and their associated costs.

In addition the alternative does not provide any substantial technical advantages over the base case multi-terminal HVdc while having some technical disadvantages.

It is therefore concluded that the alternative of providing two, two-terminal HVdc systems, one from Gull Island to Soldiers Pond and the second from Taylors Brook to Salisbury combined with new ac transmission facilities to interconnect Taylors Brook to Solders Pond is not recommended above the base case multi-terminal HVdc configuration.

2.6 Alternative 5 - Three, Two-Terminal HVdc Links

This alternative includes three, two terminal HVdc systems, one from Gull Island to Taylors Brook 1, one from Taylors Brook 2 to Soldiers Pond, and the third from Taylors Brook 3 to Salisbury. In addition to the converter stations located at Taylors Brook, an extensive ac system would have to be established there in order to interconnect the converters. The basic configuration is shown in Figure 6.

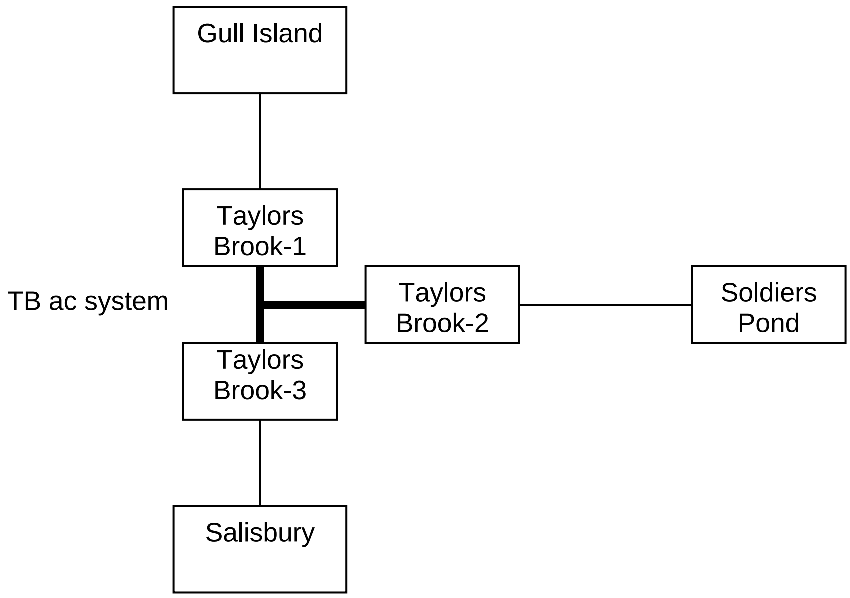

Figure 6 Alternative 5 - Three Two-Terminal HVdc Links

Nominal and overload ratings of the required terminals for this alternative are as shown in Table 21.

Table 21
Nominal and Overload Ratings for Alternative 5 (per Pole)

		Overload rating (MW)	
Location	**Nominal rating (MW)**	**10 Minute**	**Steady State**
Gull Island	800	1600 (2 pu)	1200 (1.5 pu)
Taylors Brook 1	800	1600 (2 pu)	1200 (1.5 pu)
Taylors Brook 2	400	800 (2.0 pu)	600 (1.5 pu)
Soldiers Pond	400	800 (2.0 pu)	600 (1.5 pu)
Taylors Brook 3	400	440 (1.1 pu)	440 (1.1 pu)
Salisbury	400	440 (1.1 pu)	440 (1.1 pu)
Total (per pole)	**3200**	**5680**	**4480**
Total (Bipole)	**6400**	**11360**	**8960**

These requirements represent the largest amount of installed converter capacity for all alternatives considered.

When comparing to the base case multi-terminal configuration, alternative 5 requires a total installed converter capacity with 2.0 times the nominal rating, 2.29 times the 10-minute overload rating, and 2.15 times the steady state overload rating.

2.6.1 Converter Terminal Costs

Repeating the analysis of Table 5 to Table 7, cost estimates for the converter terminals for alternative 5 are given in Table 22.

Table 22
Estimated cost of converter terminals for Alternative-5

Location	Nominal rating (MW)	10 Min. OL (MW)	Steady State OL (MW)	Cost
Gull Island (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1136 pu$
Taylors Brook 1 (per pole)	800	1600 (2.0 pu)	1200 (1.5 pu)	1136 pu$
Taylors Brook 2 (per pole)	400	800 (2.0 pu)	600 (1.5 pu)	566 pu$
Soldiers Pond (per pole)	400	800 (2.0 pu)	600 (1.5 pu)	566 pu$
Taylors Brook 3 (per pole)	400	480 (1.1 pu)	440 (1.1 pu)	400 pu$
Salisbury (per pole)	400	480 (1.1 pu)	440 (1.1 pu)	400 pu$
Total (per pole)	**3200**	**5680**	**4480**	**4204 pu$**
Total (Bipole)	**6400**	**11360**	**8960**	**8408 pu$**

When comparing the converter costs for alternative 5 to the base case multi-terminal HVdc configuration it is seen that the overall converter costs have increased by approximately 95%. This is due to the fact that there are now three separate two-terminal HVdc links with a total of six converter stations. (Note that costs of the new ac transmission required to interconnect the three HVdc links at Taylors Brook has not been factored into the above converter costs.)

2.6.2 Transmission Lines and Cables

The approximate lengths of the required overhead lines and cables in this case are given in Table 23.

Table 23
Overhead line and cable lengths for Alternative-5

Section	OHL (km)	Cable (km)
Gull Island to Strait of Belle Isle	407	
Across Strait of Belle Isle		40.7 (two poles)
Strait of Belle Isle to Taylors Brook	275	
Taylors Brook to Soldiers Pond	406	
Taylors Brook to Cape Ray	300	
Across Cabot Strait		480 (two poles)
Cost of New Brunswick to Salisbury	100	
Total	**1488**	**520.7**

Comparing the lengths of overhead lines and cables required for Alternative 5 to those required in the Base Case it is seen that Alternative 4 requires the same length of HVdc overhead line and undersea cable as the base case.

2.6.3 *Effective Short Circuit Ratio*

The effective short circuit ratios at Gull Island and Salisbury terminals are similar to the three-terminal case.

Since there are now multiple HVdc links terminating within the Newfoundland system, the MIESCR should be calculated instead of the ESCR for the converter at Soldiers Pond. However due to the weakness of the existing ac connection the MIIF factor will be small and the MIESCR is expected to be slightly less than the ESCR value calculated for the three-terminal case. Therefore no additional synchronous condensers will be required to support the HVdc converter at Soldiers Pond.

At Taylors Brook the three HVdc terminals are connected to the same bus, causing a substantial reduction in MIESCR. Even to achieve MIESCR = 1 (very low) the ac system short circuit capacity (SCC) must be more than 4160MVA. Given the low strength of the existing system at this bus majority of this capacity must come from new synchronous condensers. Therefore a very large number of additional synchronous condensers will be required to support the three HVdc terminals at Taylors Brook.

2.6.4 *Advantages*

The following is a list of advantages of this alternative as compared to the base case multi-terminal configuration:

- The three HVdc links could be built in stages, with the Gull Island to Taylors Brook and The Taylors Brook to Soldiers Pond links built prior to the Taylors Brook to Salisbury link. However, it is most likely that the Gull Island to Taylors Brook HVdc link would have to be built initially to its final capacity since staging of this two terminal link would not present substantial economic benefits.

- Only conventional two-terminal HVdc links are used therefore some of the challenges associated with the multi-terminal option are avoided. HVdc controls are less complicated compared to the base case multi-terminal HVdc system.
- The effect of the long dc cable is removed from the circuit between Gull Island and Soldiers Pond and its performance.
- If the Gull Island to Soldiers Pond link is unavailable then power can still be supplied to the Newfoundland system by operating Salisbury as a rectifier and Taylors Brook as an inverter.

2.6.5 Disadvantages

The following is a list of disadvantages of this alternative as compared to the base case multi-terminal configuration:

- This alternative requires a total of 8960MW of installed converter capacity which is unreasonably high, increasing the cost of the converter station costs by 95%.
- The three separate HVdc links which terminate at Taylors Brook would results in a multi-infeed HVdc scenario.
- Although the three HVdc links are effectively independent of one another, the performance of one will greatly impact the performance of the others.
- The Multi-Infeed ESCR (MIESCR) at Taylors Brook is very low, requiring to the need to install a very large number of synchronous condensers.
- A large sub-station and ac system would have to be established at Taylors Brook.
- Increased operating losses due to the additional filters and need to convert dc to ac and again from ac to dc at Taylors Brook.
- Increased maintenance due to the fact that there are now three new converter stations at Taylors Brook.
- Increased spares requirements due to the different ratings of converter equipment at the three terminals in Taylors Brook.

2.6.6 Summary

Based on the results of this cursory evaluation it is seen that when compared to the base case multi-terminal HVdc configuration the alternative of three, two terminal HVdc links, one from Gull Island to Taylors Brook, one from Taylors Brook to Soldiers Pond, and the third from Taylors Brook to Salisbury will result in:

- drastically increased converter costs;

- no reduction in HVdc overhead line or cable lengths;
- new ac transmission facilities at Taylors Brook to interconnect the three HVdc terminals located there; and
- a very large number of additional synchronous condensers within the Newfoundland system and their associated costs.

In addition the alternative does not provide any substantial technical advantages over the base case multi-terminal HVdc while having some technical disadvantages.

It is therefore concluded that the alternative of providing three, two terminal HVdc links, one from Gull Island to Taylors Brook, one from Taylors Brook to Soldiers Pond, and the third from Taylors Brook to Salisbury is not recommended above the base case multi-terminal HVdc configuration.

3. Summary of Results

The cost of converter terminals, length of overhead lines and cables and relative amount of required synchronous condensers for the base case and the five alternatives are summarized in Table 24.

Table 24
Summary of Results

Case	Converter Cost		DC OH Line		DC Cable km	ac OH Line km	Need for Synchronous Condenser
	pu$	Relative to base case	km	Relative to base case			
Base	4306	1	1488	1	520	0	Low
Alt. 1	6144	1.43	1894	1.27	520	0	High
Alt. 2	3864	0.83[1]	2170	1.46	561	0	Low
Alt. 3	6144	1.43	1082	0.73	520	800	Very High
Alt. 4	6144	1.43	1488	1	520	800	Fairly High
Alt. 5	8408	1.95	1488	1	520	0	Extremely High

[1] No provision has been included to account for the fact that the total installed converter capacity at Gull Island is installed in two separate converter stations which should be expected to increase the cost as compared to installation of the entire capacity within a single converter.

Salient point of the overall comparison of the alternatives includes:

- For all alternatives except alternative 2, the total cost of converters is greater than that of the base case multi-terminal HVdc configuration.
- For all alternatives except alternative 3, the total length of HVdc overhead line and cable is equal to or greater than that of the base case multi-terminal HVdc configuration. In the case of alternatives 3 and 4, an additional 800 km of 230 kV as transmission lines are required on the island of Newfoundland.
- For all alternatives, synchronous condenser requirements within the Newfoundland ac system are equal to greater than those of the base case multi-terminal HVdc configuration.
- None of the alternatives considered provided any significant advantages as compared to the base case multi-terminal HVdc configurations while providing some disadvantages.

4. Conclusions

Based on the results of this cursory evaluation it is concluded that the base case multi-terminal HVdc configuration offers the lowest overall cost when considering the cost of converters, HVdc overhead lines and undersea cables, ac transmission lines, and synchronous condenser requirements. Furthermore, none of the alternatives considered offered any significant advantages over the base case multi-terminal HVdc configuration. Therefore it is recommended than none of the alternative configurations be considered as a preferable option to the base case multi-terminal HVdc configuration.

References

1. DC1020 HVdc System Integration Study - Transient Stability Analysis – Interim Report