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September 30, 2019

Board of Commissioners of Public Utilities
Prince Charles Building
120 Torbay Road, P.O. Box 21040
St. John's, NL A1A 5B2

Attention: Ms. Cheryl Blundon
Director of Corporate Services & Board Secretary

Dear Ms. Blundon:

Re: The Board's Investigation and Hearing into Supply Issues and Power Outages on the Island Interconnected System —Operational Studies —Stage 4

Further to Newfoundland and Labrador Hydro's correspondence of August 4, 2017, please find attached an original and twelve copies of the following documents:

- Technical Note: TN1205.66.07, "Stage 4C: Labrador Transfer Analysis," TransGrid Solutions Inc., September 25, 2019; and
- Technical Note: TN1205.71.04, "Stage 4D LIL Bipole: Transition to High Power Operation," TransGrid Solutions Inc., September 25, 2019.

Analysis associated with TransGrid Solutions' "Stage 4E: High Power Analysis" is ongoing and will be filed with the Board of Commissioners of Public Utilities in the fourth quarter of 2019.

Should you have any questions, please contact the undersigned.

Yours truly,
NEWFOUNDLAND AND LABRADOR HYDRO

SWalsh

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Senior Legal Counsel, Regulatory
SAW/sk

Encl.

cc: Gerard M. Hayes, Newfoundland Power
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ecc: Ian Kelly, Q.C., Curtis Dawe
Roberta Frampton Benefiel, Grand Riverkeeper® Labrador Inc.
Dean A. Porter, Poole Althouse
Shawn Kinsella, Teck Resources Ltd.

Engineering Support Services for:

RFI Studies

Newfoundland and Labrador Hydro

Attention: Mr. Rob Collett

Stage 4C: Labrador Transfer Analysis

Technical Note: TN1205.66.07
Date of issue: September 25, 2019

Prepared By:
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Disclaimer

This technical note was prepared by TransGrid Solutions Inc. (“TGS”), whose responsibility is limited to the scope of work as shown herein. TGS disclaims responsibility for the work of others incorporated or referenced herein. This technical note has been prepared exclusively for Newfoundland and Labrador Hydro and the project identified herein and must not be reused or modified without the prior written authorization of TGS.

Revisions

Project Name:	RFI Studies
Document Title:	Stage 4C: Labrador Transfer Analysis
Document Type:	Technical Note
Document No.:	TN1205.66.07
Last Action Date:	September 25, 2019

Rev. No.	Status	Prepared By	Checked By	Date	Comments
00	DFC	R. Brandt	R. Ostash	November 27, 2018	Draft issued for review by Hydro
01	DFC			June 7, 2019	Report updated based on comments received on March 7 2019 as well as new 150 MW ML frequency controller limit, Happy Valley fed from MFATS2, updated MFA governor model parameters, and added analysis for system restoration and OOS angle difference
02	IFC			July 23, 2019	Report updated based on comments received on July 9, 2019
03	IFA			August 8, 2019	Report updated based on comments received on August 6, 2019
04	ABC			September 3, 2019	Report updated and approved based on final comments received August 30, 2019
05	ABC			September 18, 2019	Report updated and approved based on final comments (typos) received September 4, 2019

06	IFA			September 24, 2019	Report updated based on application of MFA generator capability curves to the study results.
07	ABC			September 25, 2019	Report updated and approved based on final comments (typos) received September 25, 2019

Legend of Document Status:

Approved by Client	ABC	Issued for Approval	IFA
Draft for Comments	DFC	Issued for Information	IFI
Issued for Comments	IFC	Returned for Correction	RFC

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Appendices

1. Executive Summary

Stage 4 is the final stage of operational studies being performed to determine the system operating limits of the Newfoundland and Labrador Hydro (Hydro) Island Interconnected System (IIS) for the point in time when the 900 MW LIL bipole, the Muskrat Falls MFA generators, the Soldiers Pond synchronous condensers and the ML are in-service. The Holyrood thermal generators, the Stephenville Gas Turbine, and the Hardwoods Gas Turbine are no longer in-service, and Holyrood Unit 3 is operating as a synchronous condenser.

This report presents a study of the Labrador system to:

- assess voltage conditions with and without a 150 MVAr reactor at Muskrat Falls as 1, 2, 3 and 4 MFA generating units are placed in-service[1]
- determine the LIL power transfer limits to meet Transmission Planning Criteria over the full range of Labrador operating conditions
- determine the power transfer limits on the two parallel 315 kV lines L3101 and L3102 between Churchill Falls (CHF) and Muskrat Falls (MFA)
- investigate the isolated operation of the LIL with the Muskrat Falls generators under system conditions when the two 315 kV lines L3101 and L3102 are out-of-service
- determine the maximum angle separation that occurs at a Muskrat Falls generator during system faults, in order to provide information for out of step protection settings for the units
- investigate the procedure for system restoration of the Muskrat Falls units: 1) from Churchill Falls and 2) in isolation with the LIL and the Happy Valley load fed from MFATS2

The results of the analysis are summarized below.

1.1 LIL Transfer Limits

LIL power transfer limits are required to ensure the (n-1) steady state voltage at Muskrat Falls remains within Transmission Planning Criteria limits of 0.9 pu to 1.1 pu over the full range of Labrador operating conditions. The determining contingency for overvoltage is either loss of the 150 MVAr reactor (if it is in-service) or loss of an MFA unit. The determining contingency for undervoltage is loss of one of the two 315 kV lines between Muskrat Falls and Churchill Falls.

This study analyzed scenarios with one, two, three and four MFA generating units in-service with the objective of determining the **minimum LIL transfer limits to avoid overvoltage conditions** on the Muskrat Falls 315kV bus (Section 3), and the **maximum LIL transfer limits to avoid undervoltage conditions** on the Muskrat Falls 315kV bus (Section 4).

[1] The 150 MVAr MFA reactor is assumed to be available during the early stages of the project as MFA units are brought online. This study will identify when the reactor may be removed from service as units become available.

The 150 MVAr reactor that is currently in-service at Muskrat Falls is assumed to be available during the early stages of the project as MFA units are brought online. This study determined that the reactor is required with one MFA unit on-line but can be removed from service once two MFA units are on-line, although it aids in preventing overvoltages with two MFA units on-line. It is not required when 3 or 4 MFA units are on-line. Table 1-1 summarizes these requirements.

Table 1-1. Need for 150 MVAr Reactor

Number of MFA Units On-line	Reactor Required?	Notes
1	**YES**	In addition to reactor, minimum LIL transfer limits as defined in Table 1-2.
2	**NO**, but useful	If reactor is not in-service, minimum LIL transfer limits as defined in Table 1-2.
3	**NO**	No overvoltage concerns
4	**NO**	No overvoltage concerns

The minimum and maximum LIL power transfer limits, summarized in Table 1-2, are dependent on how many MFA units are on-line, and on how much power the MFA units are generating[2].

Please note the following with regards to Table 1-2:

- Red text means that the maximum LIL power transfer limit is less than the next filter switch-in point, therefore there is a zone in which the LIL should not operate due to chance of voltage collapse if one of the 315 kV lines is out of service.
- Blue text means that the minimum LIL power transfer limit is higher than the filter switch-out point for that number of filters (or higher than minimum LIL power at deblock), therefore there is a zone in which the LIL should not operate due to chance of overvoltage if the reactor or an MFA unit trip.
- Green text refers to the rated LIL power transfer levels associated with filter switch-in and switch-out points, i.e. normal operation.

[2] The reactive power capability of the MFA units is highly dependent on the real power generation, which has a significant impact on the overvoltages and to moderate impact on the undervoltagess at Muskrat Falls.

Table 1-2. LIL Power Transfer Limits

Number of MFA Units	Status of Reactor	Number of Filters	To avoid overvoltages		To avoid undervoltages
			MFA Output (MW)	Minimum LIL Transfer Limit (Bipole) (MW)	Maximum LIL Transfer Limit (Bipole) (MW)
1	IN	2	103-195	90	280-300*
			195-206	150	
		3	103-180	270	340-360*
			180-206	345	
		4	103-206	540	420
2	IN	2	206-412	90	315
		3		270	540
		4		540	590-620*
	OUT	2	206-380	90	315
			380-412	150	
		3	206-370	270	585
			370-412	360	
		4	206-412	540	675-730*
3	OUT	2	309-618	90	315
		3		270	585
		4		540	815-900*
4	OUT	2	412-824	90	315
		3		270	585
		4		540	900

*Maximum LIL transfer limit range over the full range of MFA generation. Please refer to Section 4 for specific details.

1.2 315 kV Power Transfer Limits

1.2.1 System Intact

1.2.1.1 Direction - Churchill Falls to Muskrat Falls

The highest power transfer in the direction from Churchill Falls to Muskrat Falls occurs during high LIL power transfer and Happy Valley load conditions. The 315 kV power transfer is also highest when MFA generation is low. The LIL power transfer limits discussed and defined in Table 1-2 are associated with varying operating points that consider the full range of MFA generation from minimum to maximum. For further details regarding the specific operating points associated with these LIL power transfer limits, including the corresponding Churchill Falls to Muskrat Falls 315 kV power transfers, please refer to Section 4.

Please note that the Churchill Falls to Muskrat Falls 315 kV power transfers reported in Section 4 are not necessarily limits themselves, but are the corresponding power transfers associated with the operating point that defines the LIL power transfer limits.

1.2.1.2 Direction – Muskrat Falls to Churchill Falls

Table 1-3 summarizes the power transfer limits in the direction from Muskrat Falls to Churchill Falls under system intact conditions when the LIL is out-of-service or operating at minimum power.

Purple-highlighted limits are required to prevent system instability if there is a three-phase fault (3PF) on one of the two 315 kV CHF-MFA lines.

Table 1-3. System intact power transfer limits on MFA-CHF 315 kV corridor

MFA Units	MFA Gen (MW)	LIL (MW)	Power Flow (MW) – MFA to CHF		
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV
4	700	0	653	654	675
3	618 (max)	0	575*	577*	593*
2	412 (max)	0	380*	381*	387*
1	206 (max)	0	179*	180*	182*
4	700	45 (min)	611	612	630
3	618 (max)	45 (min)	533*	534*	548*
2	412 (max)	45 (min)	336*	337*	342*
1	206 (max)	45 (min)	135*	137*	167*

*Maximum possible power flow with 3,2,1 MFA generators on-line. This power transfer is not at a limit.

The following additional conclusions apply for the power transfer direction from MFA to CHF:

- It is recommended to use the tuned PSS parameters identified in this study for the MFA generators. Without these tuned parameters, a poorly damped oscillation occurs under high MFA to CHF power transfer with four MFA generators on-line when there is a 3PF on L3101 or L3102.
- As opposed to limiting MFA to CHF power when all four MFA generators are on-line as shown in Table 1-3, a stable system response shall be obtained by cross-tripping the fourth MFA generator in the event that L3101 or L3102 trips. This will allow for the transfer of 824 MW from MFA to CHF, the entire output of the Muskrat Falls Generation Station. This solution still requires the tuned PSS parameters for the MFA generators to prevent a poorly damped oscillations.

1.2.2 Prior Outage L3101/L3102

If there is a prior outage of one of the two 315 kV CHF-MFA lines and the other line trips, the LIL will become isolated with the MFA generating units and Happy Valley load.

In order to maintain acceptable frequencies, Table 1-4 summarizes the CHF to MFA and MFA to CHF 315 kV power transfer limits when there is a prior outage of either L3101 or L3102.

Table 1-4. Prior outage power transfer limits on CHF-MFA 315 kV corridor

	CHF-MFA			MFA - CHF		
MFA Units	MFA Gen (MW)	LIL* (MW)	315kV Power Transfer[3] (@ MF) (MW)	MFA Gen (MW)	LIL* (MW)	315kV Power Transfer[4] (@ MF) (MW)
4	700	794	120	700	628	94
3	525	590	91	525	430	70
2	350	390	65	350	275	50
1	175	180	30	175	125	26

*for a 15 MW Happy Valley Load

The following additional conclusions apply when there is a prior outage of L3101 or L3102:

- In order for the frequency response of the resulting isolated MFA system to be stable following the loss of the second CHF-MFA 315 kV line, the "isolated mode" parameters of the WSHYDD governor model[5] need to be in place. It is recommended that this mode switch be triggered within the digital governor if the frequency excursion is beyond a +/- 0.5 Hz deadband.
- It is recommended that governor tuning be performed during commissioning to ensure that oscillations are sufficiently damped during islanded conditions.

1.3 MFA Generators Isolated with LIL

If both of the 315 kV lines between CHF and MFA are out-of-service, the MFA generators are isolated with the LIL and Happy Valley load. The following conclusions apply to this mode of operation:

- **If MFA units controlling frequency**
  If the MFA units are relied upon to control the isolated system frequency (droop = 5%), the units should be kept to their minimum loading of 103 MW. If operating at more than minimum loading, and there is a 3PF on an MFA generating unit and the unit trips, a sustained oscillation can occur in the MFA governor response of the remaining units, frequency dips below 58 Hz and the system can go unstable.
- **If LIL rectifier put into frequency control (recommended)**
  It is recommended to place the LIL in frequency control at the MFA terminal. The frequency

[3] Frequency dips to minimum of 58 Hz when the second 315 kV MFA-CHF line is lost.
[4] Frequency rises to maximum of 64 Hz (limit to ensure equipment protection not triggered) when the second 315 kV MFA-CHF line is lost.
[5] Andritz report "Governor Mathematical Model & Setting Parameters", MFA-AH-SD-3411-EL-H46-0001-01, 11 May 2018 lists the recommended "isolated mode" parameters. This study determine a better response can be obtained by changing K1 from 5.63 to 8.

controller will respond to loss of an MFA unit by reducing LIL power transfer. To avoid UFLS on the IIS following the reduction of LIL power infeed, the LIL frequency controller at the MFA terminal should be limited to a maximum of 120 MW. Under these operating conditions with the LIL frequency controller in-service at MFA, the maximum MFA unit loading is listed in Table 1-5. These limits are required to keep the isolated system frequency above 58 Hz and to avoid sustained oscillations in MFA governor response in case an MFA unit trips.

Table 1-5. MFA unit limits in isolated mode with LIL frequency control at MFA

# of MFA Units	Power limit of each MFA unit (MW)	LIL Power Transfer* (MW)
4	185	720
3	140	395
2	135	240
1	144*	120

*for a 15 MW Happy Valley Load. LIL power transfer would be less with higher Happy Valley load

When enabling the LIL frequency controller at MFA, the frequency controller that is normally enabled at the SOP terminal of the LIL should be disabled.

1.4 Labrador System Restoration

Two simple system restoration procedures are presented in Section 7:

- Option 1 - To restore the MFA 315 kV bus from Churchill Falls
- Option 2 - To restore the MFA units, the LIL and the Happy Valley load as an isolated system

1.5 Out-of-Step Protection for MFA units

It is noted that the results of transient stability studies have not indicated a requirement for out of step protection. On this basis, out of step protection is not a requirement for Muskrat Falls units. The study found the largest angle difference between the MFA generator internal angle and the MFA generator terminal bus angle was 60.5 degrees.

2. Study Models and Criteria

2.1 Labrador System

The Labrador System is the area of focus for this study. The high voltage network in the area around Muskrat Falls and Churchill Falls is shown in Figure 2-1.

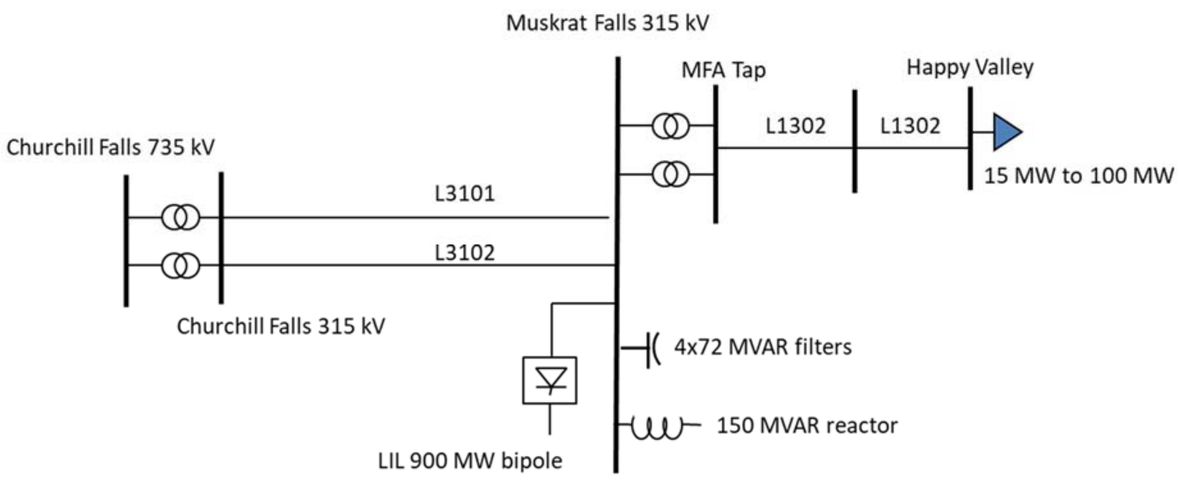

Figure 2-1. Labrador system between Muskrat Falls and Churchill Falls

2.2 LIL

The following LIL reactive power elements were available in the models:

- MFA: 4x72 MVAR filters
- SOP: 5x75 MVAR filters

The 150 MVAr MFA reactor is assumed to be available during the early stages of the project as MFA units are brought online. This study will identify when the reactor may be removed from service as units become available. Note that the reactor is not switchable and will ultimately be switched out of service once the MFA units are installed.

Table 2-1 contains the filter switch-in and switch-out points for the filters at MFA according to LIL power transfer.

Table 2-1. LIL filter switching scheme at MFA

Filters (No.) Online	Filter Capacitance (MVAR)	Total Filter Capacitance (MVAR)	Power Transmission (% of Rated Bipole Power)*		Power Transmission (MW Measured at MFACS)	
			Switch-In	Switch-Out	Switch-In	Switch-Out
2	72	144	De-Block		De-Block	
3	72	216	35	30	315.0	270.0
4	72	288	65	60	585.0	540.0

2.3 MFA governors

The MFA governor model was represented using PSSE library model WSHYDD. Appendix 1 contains the "normal mode" and "isolated mode" parameters[6] of this model.

2.4 Study Criteria

The applicable Transmission Planning Criteria for this study is summarized below:

- Steady state voltage : 0.95 pu – 1.05 pu during n-0 conditions
- Steady state voltage : 0.90 pu – 1.1 pu during n-1 conditions
- Post fault recovery voltages on the ac system shall be as follows:
  - Transient undervoltages following fault clearing should not drop below 70%
  - The duration of the voltage below 80% following fault clearing should not exceed 20 cycles
- Post fault system frequencies shall not drop below 58 Hz and shall not rise above 62 Hz
- In an islanded mode of operation, frequencies shall not exceed 64 Hz

2.5 Contingencies

Table 2-2 lists the contingencies that were considered in this study.

Table 2-2. Contingencies

Line/Generator	Fault Location	Description
L3101	MFA 315	3PF cleared in 100 ms
L3101 during a prior outage of L3102	MFA 315	3PF cleared in 100 ms. Isolates the MFA, LIL and HVY load after the line trips.
MFA unit	MFA 315	3PF cleared in 100 ms
MFA Reactor[7]	n/a	In steady state analysis only
MFA Filter	n/a	In steady state analysis only
Temporary loss of LIL bipole and pole	n/a	Temporary loss of LIL bipole and pole. Test various durations and number of restart attempts.
3PF at SOP	SOP 230	3PF cleared in 100 ms

2.6 PSSE Base Cases

Hydro provided the original set of base cases for this study.

The following assumptions were made when these base cases were created:

[6] Andritz report "Governor Mathematical Model & Setting Parameters", MFA-AH-SD-3411-EL-H46-0001-01, 11 May 2018.
[7] In cases where the MFA reactor is in service.

- Churchill Falls 735 kV voltage range can be set between 0.975 pu and 1.005 pu
- Muskrat Falls 315 kV voltage range must be held between 0.98 pu and 1.02 pu for pre-contingency scenarios. This is an operating requirement to maximize transfer limits.
- Churchill Falls exports are set in accordance with existing 735 kV limits of 5200 MW at the plant.
- Steady state operating ranges for Muskrat Falls generators are 103 MW to 206 MW[8]
- LIL power transfer can varied between minimum and maximum limits based on the total plant output of the Muskrat Falls Plant, as determined by this study

[8] As per direction from the Muskrat Falls Generation Engineering group.

3. LIL Transfer Limits - Muskrat Falls Overvoltage Considerations

Analysis was performed to assess potential overvoltage conditions on the 315 kV system due to the charging effect of the transmission lines and the filters at Muskrat Falls. A 150 MVAr MFA reactor is currently available and will remain in service during the early stages of the project as MFA units are brought online. This study will identify when the reactor may be removed from service as units become available as well as any long term operational limitations.

The contingency that results in the highest voltages at Muskrat Falls is loss of the MFA reactor. If the MFA reactor is not in-service, the next most limiting contingency for overvoltage is loss of an MFA generating unit.

Worst case system conditions were analysed at LIL filter switch-out points, with the LIL rectifier firing angle set near the minimum angle of 10 degrees to minimize LIL reactive power consumption. The CHF 735 kV voltage was set to the maximum of 1.005 pu. The Happy Valley load was set to the minimum value of 15 MW, fed from MFATS2.

In all cases, the 315 kV bus voltage at MFA shall be held in the range of 0.98 to 1.02 per unit. This serves to maximize transfer limits on the 315 kV system.

The analysis was performed for scenarios with one, two, three and four MFA generating units in-service with the objective to determine the **minimum** LIL transfer limits to avoid over-voltage conditions on the Muskrat Falls 315kV bus. Section 4 outlines the analysis performed to determine the **maximum** LIL transfer limits to avoid under-voltage conditions on the Muskrat Falls 315kV bus.

3.1 One MFA Unit In-Service

Table 3-1 summarizes the highest MFA voltages that were observed for the scenario with one MFA generating unit in-service when the reactor is lost. Worst case overvoltage conditions occur when the MFA unit is operating at maximum power (206 MW) since the unit's reactive power absorption capability is most limited at full output.

Table 3-1. Highest MFA Voltage – One MFA unit in-service

LIL Power (MW)	MFA filters	Reactor	MFA Voltage (pu) (Loss of Reactor)
540*	4	IN	1.080
345	3		1.101
270*	3		1.131
150	2		1.103
90	2		1.114

*MFA filter switch-out point

It is evident from the overvoltages listed in Table 3-1 that the MFA reactor must be in-service if there is only one MFA unit on-line. Even with the reactor in-service, the n-1 voltage criteria (1.1 pu) will be violated if the reactor is lost under certain operating conditions. For example, overvoltages occur near the switch-out point for the third filter (LIL 270 MW), and near minimum power (LIL 90 MW) with two filters in-service when the MFA unit is operating at 206 MW as shown in red text.

3.1.1 Mitigation for Overvoltage with One MFA Unit

Based on the results in Table 3-1, operation of the LIL with only one MFA unit in service will result in violations to Transmission Planning Criteria. On this basis, further analysis was performed to assess alternatives to mitigate the overvoltages, including:

1. Taking a 315 kV MFA-CHF line out of service (to reduce charging)
2. Placing operating restrictions on the LIL

Reactor In-Service
As detailed in the Section 3.1.1.2 below, operating the LIL at a minimum power transfer level was found to successfully mitigate the overvoltages when only one MFA unit is on-line.

Reactor Out-of-Service
As detailed in Sections 3.1.1.1 and 3.1.1.2, neither mitigation option was able to successfully mitigate the overvoltages when only one MFA unit is on-line and the reactor is out-of-service. On that basis, the operation of the LIL is not permitted when there is only one unit in service at Muskrat Falls and the reactor is out of service.

3.1.1.1 Taking 315 kV line out-of-service

In order to eliminate some of the charging from the 315 kV MFA-CHF lines (depending on the operating point), the worst case overvoltage scenario was tested to see if taking one of the MFA-CHF lines out-of-service would reduce the overvoltage. However, the overvoltage was not impacted at this operating point when the 315 kV line was removed from service.

3.1.1.2 Operating LIL at a minimum level

The LIL deblocks with two 72 MVAr filters in-service at MFA. To be able to operate with two filters in-service, the LIL must be transferring a minimum level of power in order to prevent overvoltages, as detailed below:

Reactor In-Service
With the reactor in-service, the minimum LIL Bipole transfer limit would be dependent on the output of the MFA unit in-service as shown in Table 3-2.

Table 3-2. Minimum LIL Transfer Limits – One MFA Unit

Number of MFA Filters	MFA Output (MW)	Minimum LIL Transfer Limit (Bipole)
2	103-195	90*
	195-206	150

Number of MFA Filters	MFA Output (MW)	Minimum LIL Transfer Limit (Bipole)
3	103-180	270*
	180-206	345
4	103-206	540*
*Limit based on LIL filter switching scheme ("Switch-Out")		

Reactor Out-of-Service
With the reactor out-of-service, there are no minimum LIL transfer levels that are able to avoid overvoltages with only one MFA unit on-line. Therefore, the reactor must be in-service when one MFA unit is online.

3.2 Two MFA Units In-Service

Table 3-3 summarizes the highest MFA voltages that were observed for the scenario with two MFA generating units in-service.

Table 3-3. Highest MFA Voltage – Two MFA units in-service

LIL Power (MW)	MFA filters	Reactor	MFA Voltage (pu)	
			Max MFA Gen (412 MW)	
			Loss Reactor	Loss MFA Unit
540	4	IN	1.061	1.024
270	3		1.067	1.048
90	2		1.062	1.044
540	4	OUT	N/A	1.072
360	3		N/A	1.099
270	3		N/A	1.131
150	2		N/A	1.103
90	2		N/A	1.114

With the reactor in-service, there are no steady state high voltage violations.

With the reactor out-of-service, n-1 (1.1 pu) voltage criteria are violated if an MFA unit is lost under certain operating conditions. For example, overvoltages occur near the switch-out point for the third filter (LIL 270 MW), and near minimum power (LIL 90 MW) with two filters in-service when the MFA units are operating at full output (412 MW) as shown in red text in Table 3-3.

3.2.1 Mitigation for Overvoltage with Two MFA Units (No Reactor)

Based on the results in Table 3-3, operation of the LIL with two MFA units in service will result in violations to Transmission Planning Criteria if the reactor is out of service. On this basis, further analysis was performed to assess operational limitations (operating the LIL at a minimum power transfer level) to mitigate the overvoltages if the MFA units are operating at maximum output.

3.2.1.1 Operating LIL at a minimum level

The LIL deblocks with two 72 MVAr filters at MFA. In order to meet the 1.1 pu n-1 voltage criteria if an MFA unit trips, and to be able to operate with two filters in-service and the reactor out-of-service, the LIL would need to be operated at a minimum power transfers of 150 MW with two filters in-service and 360 MW with three filters in-service, if the MFA units are operating at maximum output. Table 3-4 summarizes the allowable LIL operating ranges for number of filters in-service.

Table 3-4. Minimum LIL Transfer Limits – Two MFA Units

Status of Reactor	Number of MFA Filters	MFA Output (MW)	Minimum LIL Transfer Limit (Bipole)
IN	2	206-412	90*
	3		270*
	4		540*
OUT	2	206-380	90*
		380-412	150
	3	206-370	270*
		370-412	360
	4	206-412	540*
*Limit based on LIL filter switching scheme ("Switch-Out")			

3.3 Three MFA Units In-Service

Table 3-5 summarizes the highest MFA voltages that were observed for the scenario with three MFA generating units in-service.

Table 3-5. Highest MFA Voltage – Three MFA units in-service

LIL Power (MW)	MFA filters	Reactor	MFA Voltage (pu) Max MFA Gen (618 MW) (Loss MFA Unit)
540	4	OUT	1.062
270	3		1.067
45	2		1.062

Based on the results in Table 3-5, the MFA reactor does not need to be in-service if there are three MFA generating units in-service.

3.4 Four MFA Units In-Service

Table 3-6 summarizes the highest MFA voltages that were observed for the scenario with four MFA generating units in-service.

Table 3-6. Highest MFA Voltage – Four MFA units in-service

LIL Power (MW)	MFA filters	Reactor	MFA Voltage (pu) Max MFA Gen (824 MW) (Loss MFA Unit)
540	4	OUT	1.050
270	3		1.051
90	2		1.044

Based on the results in Table 3-6, the MFA reactor does not need to be in-service if there are four MFA generating units in-service.

4. LIL Transfer Limits - Muskrat Falls Undervoltage Considerations

Section 3 included analysis of overvoltage conditions resulting from worst-case contingencies. This section includes analysis of undervoltage conditions that arise when there are significant power flows in the Churchill Falls (CHF) to Muskrat Falls (MFA) corridor. In these cases, the most limiting contingency is loss of one of the two 315 kV CHF-MFA lines (L3101 or L3102).

4.1 Power Transfer CHF to MFA

This section evaluates power transfer from CHF to MFA, with one, two, three and four MFA generators on-line. LIL is set to maximum power, or to the limit to be defined by this study.

If one of the two 315 kV lines between MFA and CHF trips (L3101 or L3102), a steady state voltage collapse occurs if there is too much power is flowing on this 315 kV corridor. The voltage collapse occurs soon after the MFA generating units have reached their maximum reactive power output and can no longer control the voltage. Muskrat Falls 315 kV voltage range is set between 0.98 pu and 1.02 pu for pre-contingency scenarios

Worst case system conditions were analysed at LIL filter switch-in points, with the LIL rectifier firing angle set near the maximum (16 degrees) to maximize LIL reactive power consumption. CHF 735 kV voltage was set to 0.975 pu. Happy Valley load was set to a peak value of 100 MW, fed from MFATS2.

The analysis was performed for scenarios with one, two, three and four MFA generating units in-service over the range of minimum to maximum MFA generation to determine the **maximum** LIL transfer limits. When voltage collapse was observed, power transfer on the LIL, and hence between CHF and MFA, was limited to prevent the voltage collapse.

The most limiting condition in the CHF to MFA power direction was the steady state voltage collapse. Transient stability concerns were not observed.

4.1.1 One MFA Unit

With one MFA unit and the reactor in-service, LIL power transfer is limited to a maximum of 360 MW due to undervoltage considerations as shown in Table 4-1.

Table 4-1. Power Transfer Limits – One MFA unit in-service

LIL Power (MW)	MFA filters	Reactor	Power Flow (MW) – CHF to MFA			MFA Voltage (pu)
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV	
At Max MFA Generation (206 MW)						
420	4	IN	338	337	326	0.975*
340	3		253	252	246	0.973*
280	2		191	190	186	0.939*
At Min MFA Generation (103 MW)						
420	4	IN	450	449	429	0.950*

360	3		384	383	369	0.948*
300	2		320	319	309	0.940*

*Operating point associated with maximum LIL power transfer before voltage collapse occurs

As per Section 3, operation of the LIL is not permitted with only one MFA unit in service and the reactor out-of-service. In such a case, HVY loads may be supplied from Churchill Falls and are unrestricted.

4.1.2 Two MFA Units

Operation limits for the LIL with two MFA units in service and the MFA reactor in service are summarized in Table 4-2.

Table 4-2. Power Transfer Limits – Two MFA units in-service (Reactor IN)

LIL Power (MW)	MFA filters	Reactor	Power Flow (MW) – CHF to MFA			MFA Voltage (pu)
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV	
At Max MFA Generation (412 MW)						
620	4	IN	334	333	322	0.932*
540	3		259	258	251	0.932*
315	2		16	16	15	0.970
At Min MFA Generation (206 MW)						
590	4	IN	527	526	497	0.907*
545	3		476	476	452	0.910*
315	2		227	226	221	0.948

*Operating point associated with maximum LIL power transfer before voltage collapse occurs

Operation limits for the LIL with two MFA units in service without the MFA reactor are summarized in Table 4-3.

Table 4-3. Power Transfer Limits – Two MFA units in-service (Reactor OUT)

LIL Power (MW)	MFA filters	Reactor	Power Flow (MW) – CHF to MFA			MFA Voltage (pu)
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV	
At Max MFA Generation (412 MW)						
730	4	OUT	453	452	432	0.935*
585	3		295	294	286	0.955
315	2		16	16	15	0.985
At Min MFA Generation (206 MW)						
675	4	OUT	626	625	582	0.906*
585	3		520	518	491	0.930
315	2		227	226	221	0.981

*Operating point associated with maximum LIL power transfer before voltage collapse occurs

4.1.3 Three MFA Units

With three MFA units and the MFA reactor out-of-service, LIL power transfer is limited to a maximum of 815 MW (at minimum MFA generation of 309 MW). If MFA generation is 585 MW or higher, then the LIL can transfer rated power of 900 MW as shown in Table 4-4. Corresponding CHF to MFA power flows are also shown.

Table 4-4. Power Transfer Limits – Three MFA units in-service

LIL Power (MW)	MFA filters	Reactor	Power Flow (MW) – CHF to MFA			MFA Voltage (pu)
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV	
At Max MFA Generation (618 MW)						
900	4	OUT	415	414	397	0.934
585	3		82	81	81	0.974
315	2		-185	-187	-190	0.981
At Min MFA Generation (309 MW)						
815	4	OUT	672	671	620	0.907*
585	3		405	404	388	0.960
315	2		120	119	118	0.984
Minimum MFA Generation (585 MW) needed to transfer 900 MW on LIL						
900	4	OUT	451	450	430	0.932*

*Operating point associated with maximum LIL power transfer before voltage collapse occurs

4.1.4 Four MFA Units

With four MFA units and the MFA reactor out-of-service, the LIL can transfer rated power of 900 MW as shown in Table 4-5. Corresponding CHF to MFA power flows are also shown.

Table 4-5. Power Transfer Limits – Four MFA units in-service

LIL Power (MW)	MFA filters	Reactor	Power Flow (MW) – CHF to MFA			MFA Voltage (pu)
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV	
At Max MFA Generation (824 MW)						
900	4	OUT	196	195	192	0.964
585	3	OUT	-122	-123	-125	0.982
315	2	OUT	-380	-381	-396	0.982
At Min MFA Generation (412 MW)						
900	4	OUT	647	645	602	0.925
585	3	OUT	295	294	286	0.979
315	2	OUT	16	15	15	0.994

4.2 Power Transfer MFA to CHF

Cases representing power transfer in the direction from MFA to CHF were evaluated with the LIL out-of-service or operating at minimum power transfer, and with the MFA generators operating at maximum power, or at the limit determined in this study.

Table 4-6 summarizes the MFA to CHF power transfer limits. Purple-highlighted rows depict the cases where the MFA-CHF power transfer had to be reduced from the base cases that were provided. The cases with three or fewer MFA units in-service at maximum power had no issues. The cases with four

MFA units in-service resulted in MFA to CHF power transfer levels that had to be limited to avoid instability following a 3PF on one of the two 315 kV CHF-MFA lines, as further discussed below.

The limits provided in Table 4-6 could potentially become more restrictive depending on the final results of Hydro Quebec's Operational Studies.

Table 4-6. Power transfer limits – MFA to CHF

315kV Flow	MFA Units	MFA Gen (MW)	LIL (MW)	Power Flow (MW) – MFA to CHF at CHF 735 kV	at CHF 315 kV	at MFA 315 kV
To CHF	4	700	0	653	654	675
To CHF	3	618 (max)	0	575*	577*	593*
To CHF	2	412 (max)	0	380*	381*	387*
To CHF	1	206 (max)	0	179*	180*	182*
To CHF	4	700	45 (min)	611	612	630
To CHF	3	618 (max)	45 (min)	533*	534*	548*
To CHF	2	412 (max)	45 (min)	336*	337*	342*
To CHF	1	206 (max)	45 (min)	135*	137*	167*

*Maximum possible power flow with 3,2,1 MFA generators on-line. This power transfer is not at a limit.

The cases with four MFA units were unstable unless the power transfer from MFA to CHF was reduced to the levels shown in Table 4-6. And, even though these cases were stable at reduced power transfer levels, poorly damped oscillations were observed as shown in Figure 4-1.

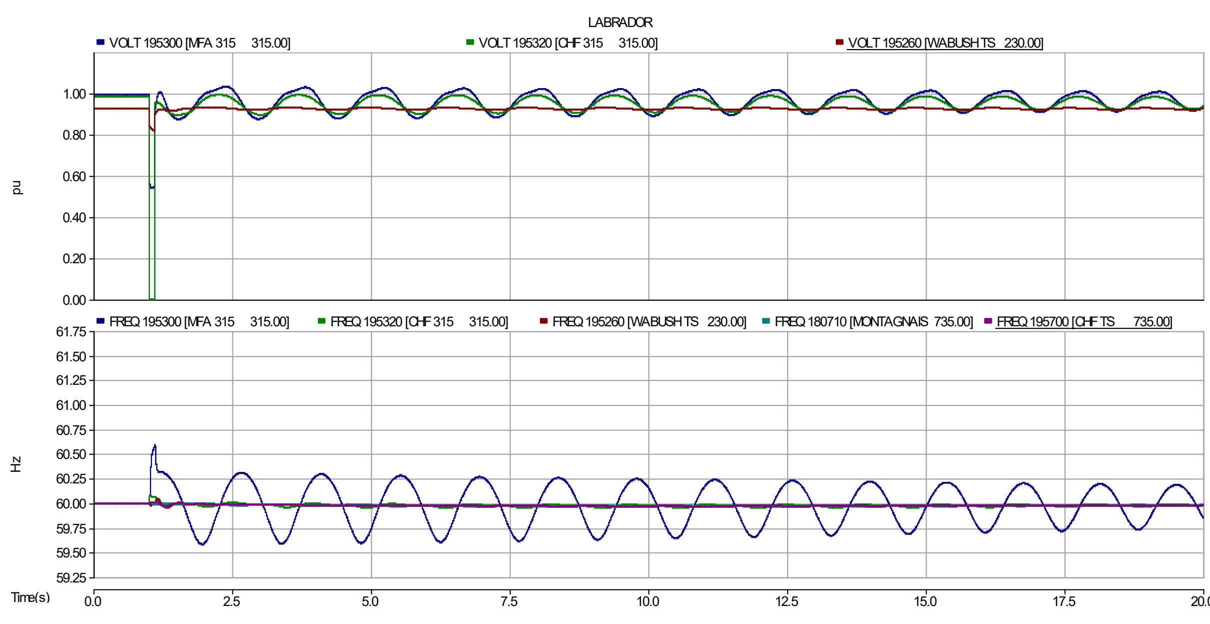

Figure 4-1. 3PF on L3101 – 4 MFA units on-line

The MFA generator power system stabilizers (PSS) were tuned to improve the damping of the oscillations as shown in Figure 4-2. The tuned parameters used in the PSS are provided in Appendix 2.

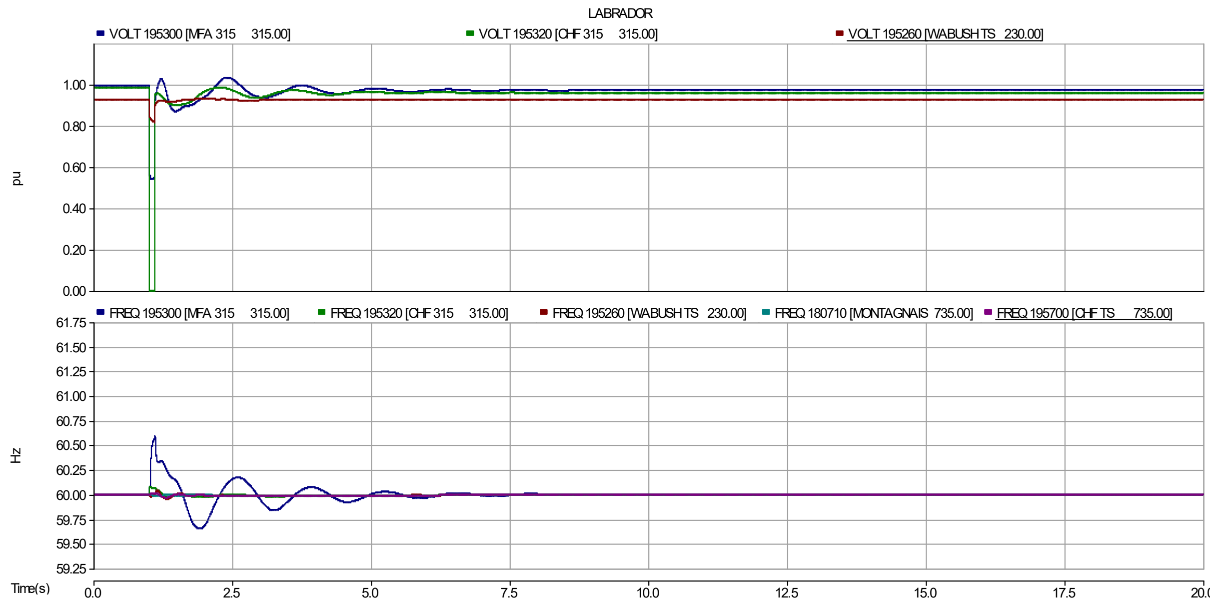

Figure 4-2. 3PF on L3101 with tuned PSS – 4 MFA units on-line

4.2.1 Use of MFA Generator Cross-Tripping to Avoid Power Transfer Limits

As opposed to limiting MFA to CHF power transfer when four MFA generators are on-line, a stable system response shall be obtained by cross-tripping one of the four MFA generators when one of the 315 kV CHF-MFA lines trips. With this cross-tripping scheme in place, MFA generation would not have to be limited when all four units are on-line, as shown in Table 4-6. Please note that the generator cross-tripping option still requires the tuned PSS parameters to prevent the poorly damping oscillations.

Table 4-6. Power transfer limits – MFA to CHF with cross-tripping

MFA Units	MFA Gen (MW)	LIL (MW)	Power Flow (MW) – MFA to CHF		
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV
4	824 (max)	0	767	769	798
4	824 (max)	45 (min)	726	728	753

5. Prior Outage 315 kV MFA-CHF Line

If there is a prior outage of one of the 315 kV MFA-CHF lines (L3101 or L3102), and if the second 315 kV MFA-CHF line trips, the MFA generators become isolated with the LIL and the Happy Valley load.

To maintain acceptable frequencies if the second 315 kV line trips and to maintain stability in the isolated system, the pre-contingency power flow on the 315 kV line must be limited based on the number of MFA units that are on-line.

Table 5-2 lists the power flow limits in the direction from CHF to MFA to keep the frequency above 58 Hz.

Table 5-1. Prior Outage L3101 or L3102. CHF - MFA power transfer limits

315kV Flow	MFA Units	Maximum MFA Generation (MW)	Maximum Corresponding LIL Power* (MW)	Power Flow (MW) – CHF to MFA		
				at CHF 735 kV	at CHF 315 kV	at MFA 315 kV
To MF	4	700	794	123	122	120
To MF	3	525	590	92	91	91
To MF	2	350	390	66	65	65
To MF	1	175	180	30	30	30

*for a 15 MW Happy Valley Load. LIL power transfer would be less with higher Happy Valley load

Table 5-2 lists the power flow limits in the direction from MFA to CHF to keep the frequency below 64 Hz to ensure that equipment protection is not triggered.

Table 5-2. Prior Outage L3101 or L3102. MFA - CHF power transfer limits

315kV Flow	MFA Units	Maximum MFA Generation (MW)	Minimum Corresponding LIL Power* (MW)	Maximum Power Flow (MW) – MFA to CHF		
				at CHF 735 kV	at CHF 315 kV	at MFA 315 kV
To CHF	4	700	580	92	93	94
To CHF	3	525	430	68	69	70
To CHF	2	350	275	49	50	50
To CHF	1	175	125	24	25	26

*for a 15 MW Happy Valley Load. Minimum LIL power transfer would be less with higher Happy Valley load

It is noted that study results observed oscillations in the MFA governor response during contingencies that resulted in the islanding. An example of a 3PF on L3102 (during a prior outage of L3101) is shown in Figure 5-1. This example shows the system response when moving into isolated mode of operation, with pre-contingency CHF to MFA power flow of 120 MW and four MFA units on-line. Please note the simulation time is 200 seconds. The frequency of the oscillation is approximately 0.045 Hz. It is recommended that normal and isolated mode governor responses be verified and tuned during commissioning to ensure acceptable performance.

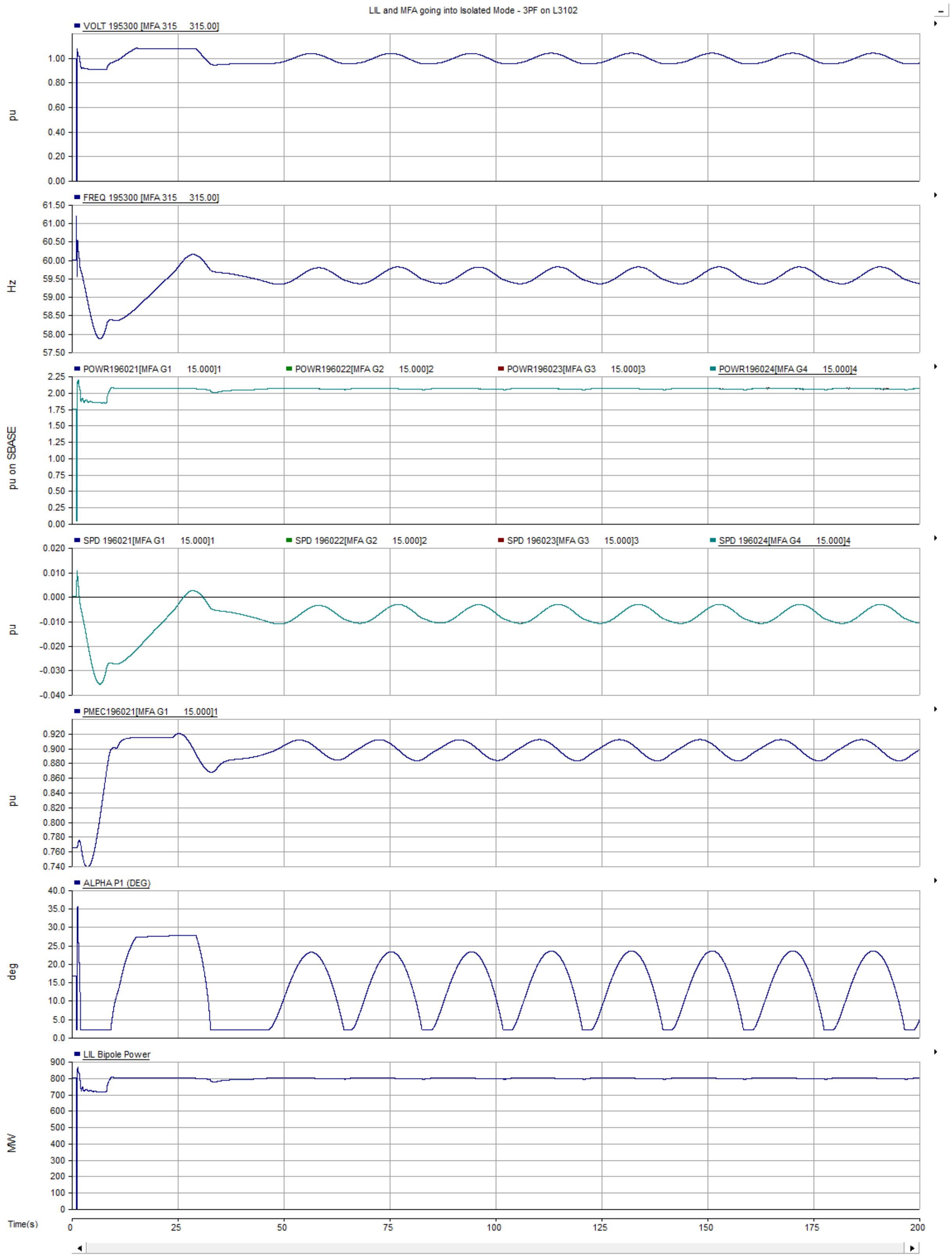

Figure 5-1. 3PF L3012 – LIL and MFA transition into isolated mode (15 MW HVY load)

The following additional conclusions are made regarding the transition into isolated mode:

- In order for the frequency response of the resulting isolated MFA system to be stable following the loss of the second CHF-MFA 315 kV line, the "isolated mode" parameters of the WSHYDD governor model[9] need to be in place. It is recommended that this mode switch be triggered within the digital governor if the frequency excursion is beyond a +/- 0.5 Hz deadband.
- It is recommended that governor tuning be performed during commissioning to ensure that oscillations are sufficiently damped during islanded conditions.

[9] Andritz report "Governor Mathematical Model & Setting Parameters", MFA-AH-SD-3411-EL-H46-0001-01, 11 May 2018 lists the recommended "isolated mode" parameters. This study determined that a better response can be obtained by changing K1 from 5.63 to 8.

6. MFA Isolated with the LIL

The following three disturbances were simulated with the MFA, LIL and HVY load operating in isolation, in order to determine the best operating methodology for this mode of operation:

1. 3PF and loss of an MFA unit
2. 3PF at SOP
3. LIL temporary pole and bipole outage

6.1 3PF MFA generating unit

6.1.1 MFA units controlling isolated system frequency

In order for the isolated system frequency to remain above 58 Hz, it is recommended that MFA generating units be limited to minimum loading values of 103 MW if the MFA generating units are relied upon to control the isolated system frequency. Additionally, the same sustained oscillations discussed in Section 5 are observed in the isolated system following a 3PF and loss of a unit when the Happy Valley load is light, as shown in Figure 6-1. As discussed above, generator controls will be tuned during commissioning to ensure acceptable system behavior.

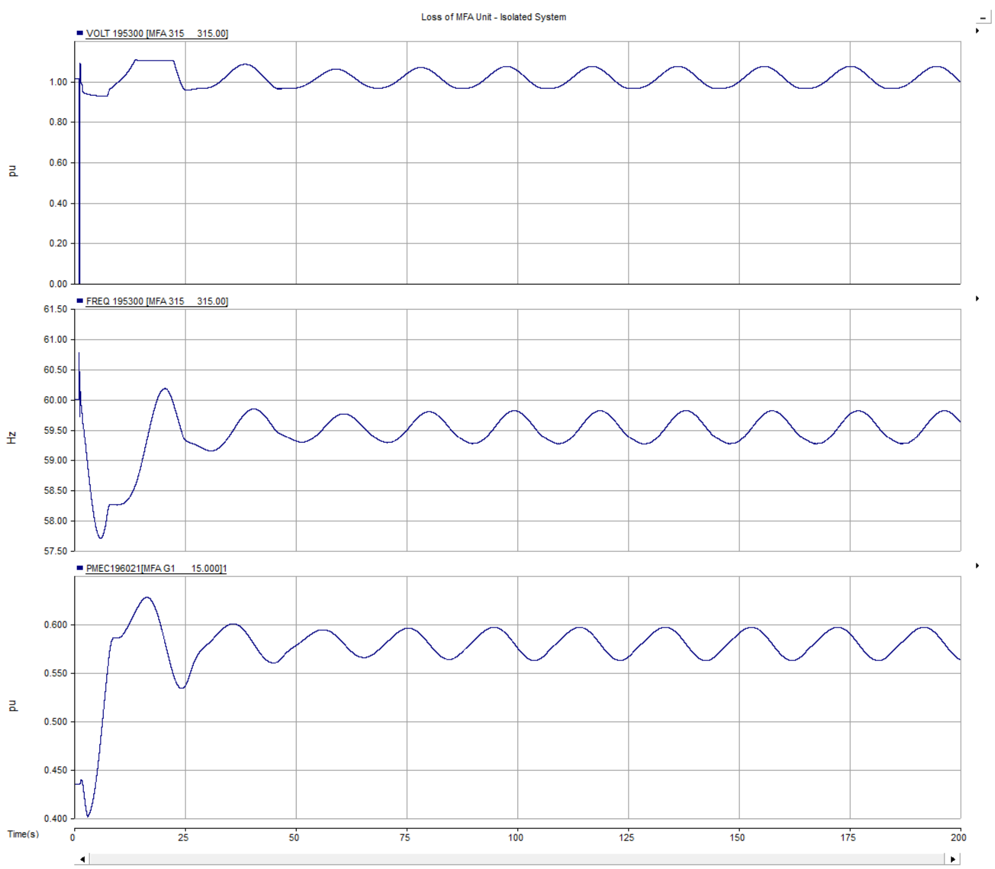

Figure 6-1. 3PF MFA generating unit (100 MW). 4 units on-line. HVY load 15 MW.

6.1.2 LIL controlling isolated system frequency

Normally, the LIL frequency controller will be enabled at the SOP inverter end of the link. However, it is recommended to place the MFA terminal of the LIL into frequency control (and disable it at the SOP end).

In order to avoid customer impact for loss of an MFA unit when operating in isolated mode, the limits of the LIL frequency controller at the MFA terminal should be set such that a reduction in LIL power order would not result in underfrequency load shedding (UFLS) on the IIS. A previous Stage 3 operational study[10] showed that under worst case system conditions (light load), the IIS can experience loss of 122 MW of LIL infeed without triggering UFLS, assuming that the ML frequency controller is in-service (and the SOP LIL frequency controller is out-of-service).

Therefore, the LIL frequency controller at the MFA terminal was set to have limits of +/-120 MW, with a deadband of +/- 0.05 Hz. With these settings, it was determined that the maximum loading of an individual MFA unit could be increased to the values listed in Table 6-1, depending on the number of MFA generating units on-line.

Adhering to the limits in Table 6-1 keeps the frequency above 58 Hz. Note that if there is only one MFA unit on-line and it trips, the isolated system cannot survive since there is no generation left in the isolated system. In this case, the MFA unit is limited such that loss of the isolated system including the LIL does not result in UFLS on the IIS, i.e. there should be a maximum power transfer of 120 MW on the LIL.

Table 6-1. Maximum MFA unit loading in isolated mode (LIL in frequency control at MFA)

# of MFA Units	Power of each MFA unit (MW)	LIL Power Transfer* (MW)
4	185	720
3	140	395
2	135	240
1**	144*	120

*for a 15 MW Happy Valley Load. LIL power transfer would be less with higher Happy Valley load

**only possible if operating with 1x72 MVAR filter at MFA, otherwise voltage is > 1.05 pu

Figure 6-2 shows an example of the response of the isolated MFA system with the LIL frequency controller enabled at MFA and for loss of an MFA unit operating at 185 MW when there are four MFA units on-line, with the LIL transferring 720 MW (Happy Valley load is 15 MW).

[10] TGS Report TN1205.64.01, “Stage 3: LIL and ML Transfer Limits – Updated”, October 2 2018. Updated Excel spreadsheets with updated LIL transfer limits to avoid UFLS were provided during May 2019.

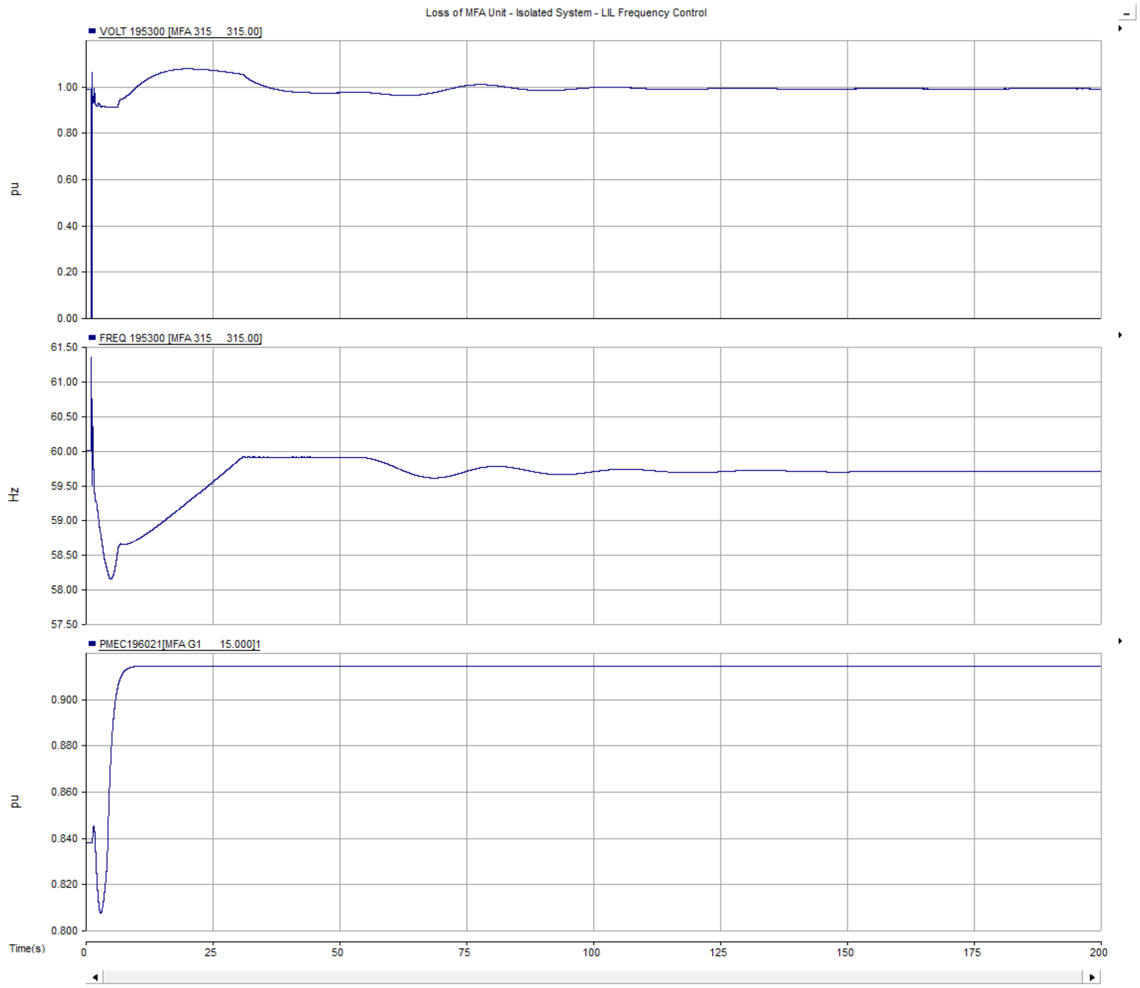

Figure 6-2. Loss of MFA generator at 185 MW with LIL frequency controller +/- 120 MW

6.2 3PF SOP

Next, a normally-cleared (100 ms) three-phase fault (3PF) was simulated at SOP for scenarios with 1, 2, 3 and 4 MFA units in-service, with each MFA unit operating the limit specified in Table 6-1 and the MFA terminal of the LIL operating in frequency control. A 3PF at SOP disrupts power transfer on the LIL during the fault.

There were no issues observed for the isolated MFA system response to a normally-cleared 3PF at SOP.

7. System Restoration – LIL Isolated with MFA

If there were a blackout of the Labrador system, MFA and the LIL would normally be restored from Churchill Falls. As a second option for system restoration, however, the MFA, LIL and HVY load could be restored in an isolated mode before reconnecting to Churchill Falls.

This analysis assumes that the MFA reactor is not in service.

7.1 Restoration Option 1 – MFA Restored from CHF

7.1.1 Switch in the 315 kV CHF-MFA Lines

If MFA is to be restored from Churchill Falls, the first step is to switch in the 315 kV lines from CHF to MFA (L3101 and L3102).

When switching each 315 kV line in to service, the open ended line voltage at MFA is as follows:

- L3101 – 1.075 pu
- L3102 – 1.079 pu

Since the voltage is below 1.1 pu, it is concluded that no MFA units are required to be on-line before the 315 kV lines are put in to service.

7.1.2 Switch in the LIL Filters

Prior to switching in two of the MFA filters (in order to be able to deblock the LIL), it is required to put two MFA units on-line, in order to keep the MFA 315 kV voltage below 1.1 pu. With two MFA units on-line, the voltage at MFA with two filters in-service is 1.063 pu. If only one MFA unit were on-line, the voltage would be 1.135 pu.

7.1.3 Add Load

As soon as Muskrat Falls is connected to Churchill Falls, there are no restrictions in energizing the Happy Valley load or deblocking the LIL in terms of underfrequency.

7.2 Restoration Option 2 - LIL Isolated with MFA

This section of the report presents a possible system restoration procedure for the second option of restoring the LIL, HVY and MFA as an isolated system.

This analysis assumes that one MFA generating unit has already been started and is supplying station service load only.

7.2.1 Step 1 – Restore Happy Valley Load

The first step to energize line 138 kV transmission line L1302 Happy Valley Terminal Station. The next step is to energize the transformers connecting to the 25 kV HVY bus. Following this, 14 MW of load at HVY can be added, which results in a frequency dip to 58 Hz at the MFA 315 kV bus, as shown in Figure 7-1.

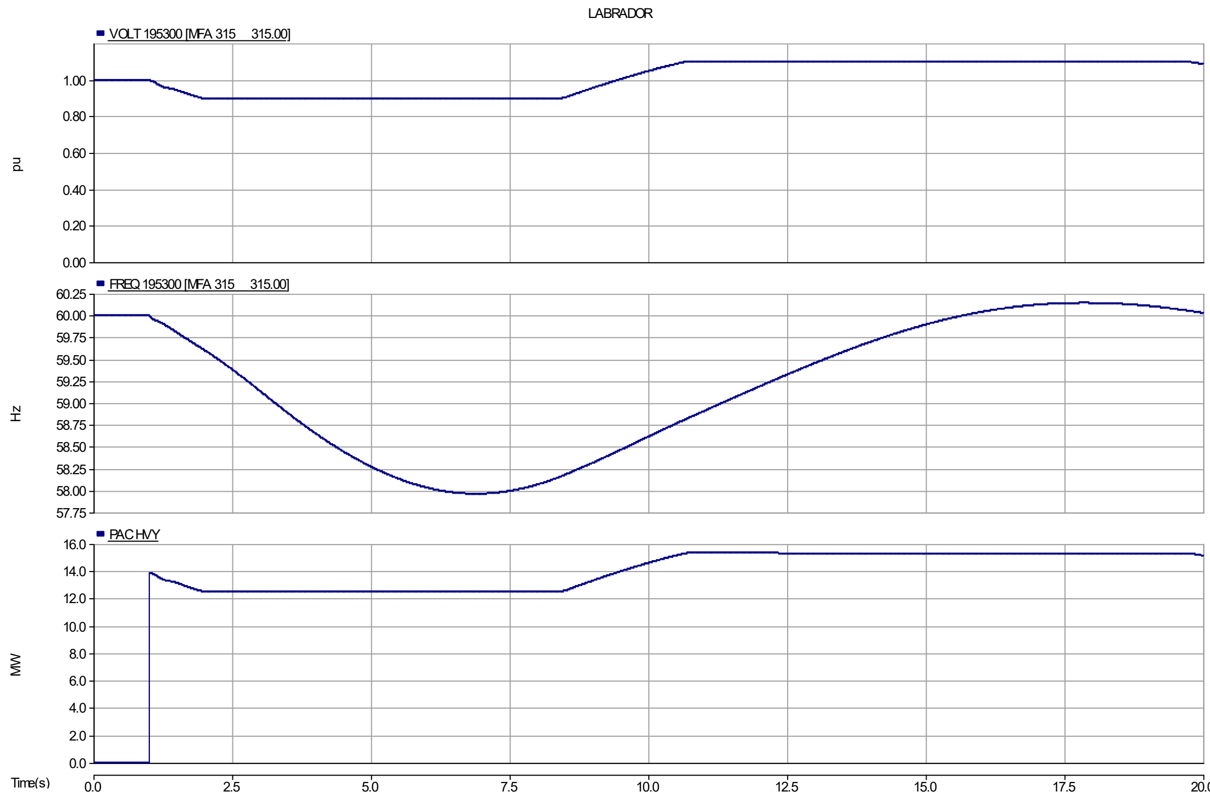

Figure 7-1. 14 MW load added at HVY

7.2.2 Step 2 – Add 2nd MFA Unit and More HVY Load

Next, the second MFA generator was put into service.

After the second unit is in-service, a 24 MW block of load at HVY can be restored, which again causes the frequency to dip to 58 Hz at MFA 315 kV bus as shown in Figure 7-2.

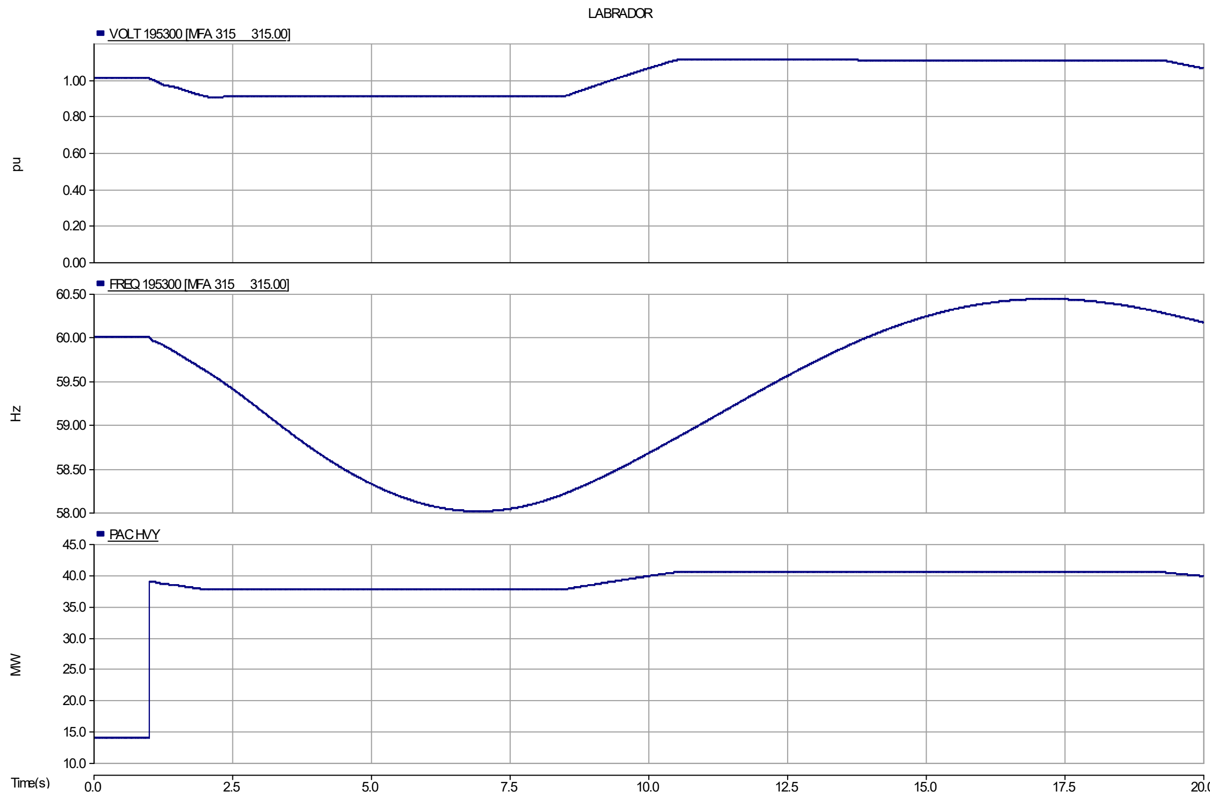

Figure 7-2. HVY load increased by 24 MW, up to a total of 39 MW

Once the system has settled, a 28 MW block of HVY load can be restored to further increase the load to a total of 67 MW, as illustrated in the plots below. This step causes the frequency to dip to 58 Hz as shown in Figure 7-3. At this point, the load at HVY may be increased as the third and fourth units are brought online at MFA.

As stated in Section 2.6, MFA units have a minimum loading limit of 103 MW under normal operation. To facilitate system restoration, consideration may be given to loading units to a value lower than this limit for short durations. Such decisions would be made at the discretion of plant personnel and would be dependent on loading conditions.

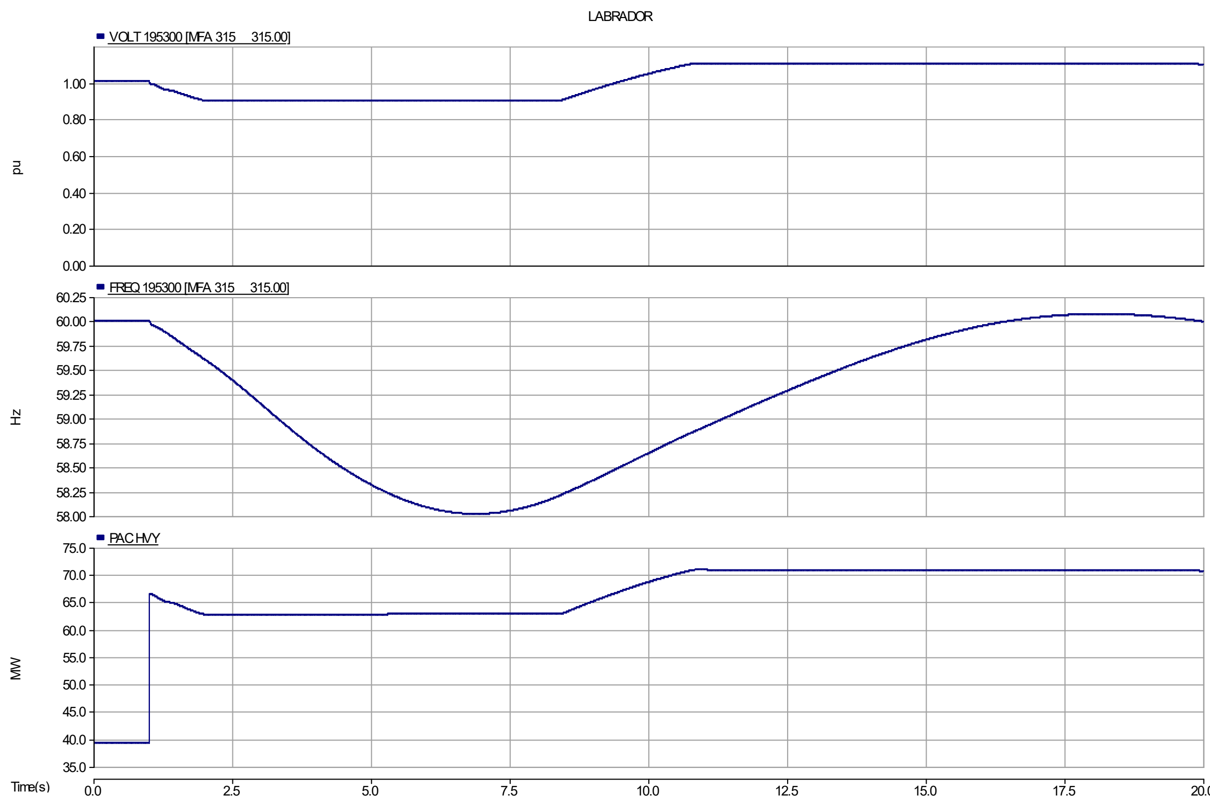

Figure 7-3. HVY load increased to 67 MW

7.2.3 Restoring LIL and filters

The first step in restoring the LIL is to switch the first filter at MFA into service, followed by the second filter.

The first pole of LIL is then de-blocked at 45 MW, which causes the frequency to drop to 58.75 Hz, as shown in Figure 7-4.

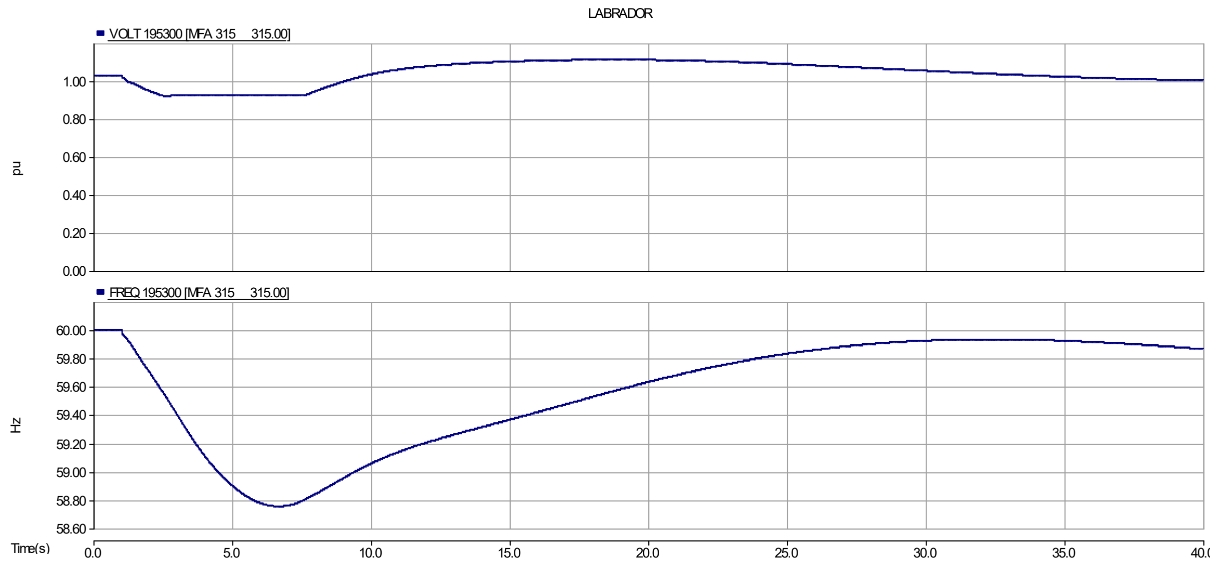

Figure 7-4. LIL pole de-blocked at 45 MW

The second pole of the LIL pole is then de-blocked at 45 MW, which causes the frequency to dip to 59.15 Hz, as shown in Figure 7-5.

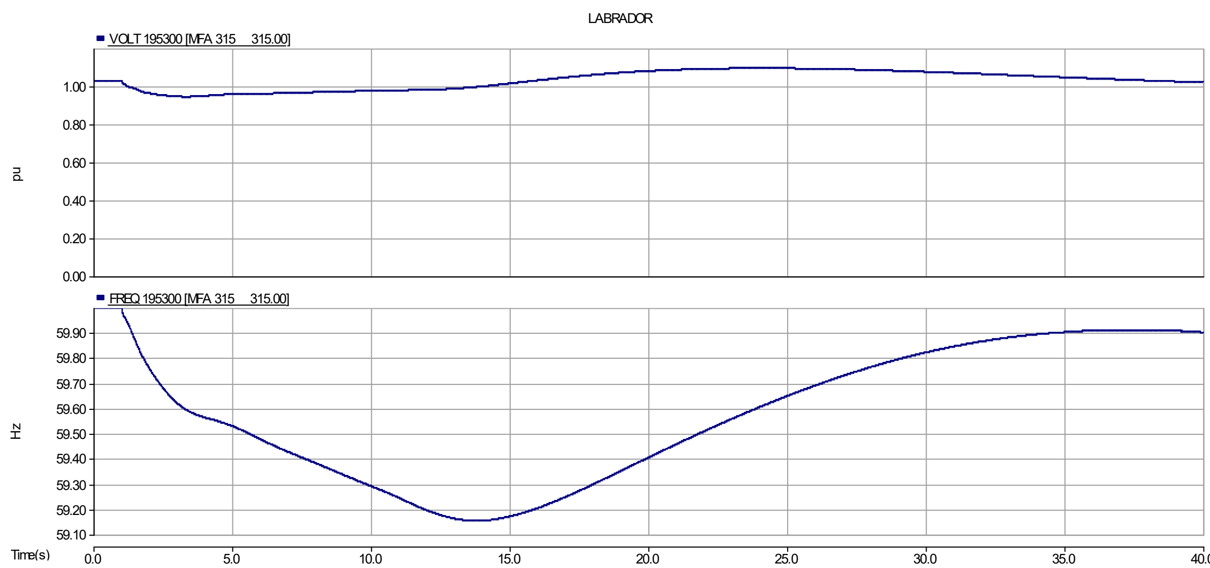

Figure 7-5. De-blocking LIL pole 2 at 45 MW

7.2.4 Ramping the MFA Generator Power

Finally, the MFA generators were ramped up to 175 MW each, with the LIL operating in frequency control at the MFA terminal, allowing it to follow the generator power ramp up. In order to demonstrate the LIL's ability to follow the power output of the MFA generators, a simulation was run to ramp the

MFA power to 700 MW in total over the course of 80 seconds of simulation as shown in Figure 7-6. In reality the power would be ramped up slower than shown.

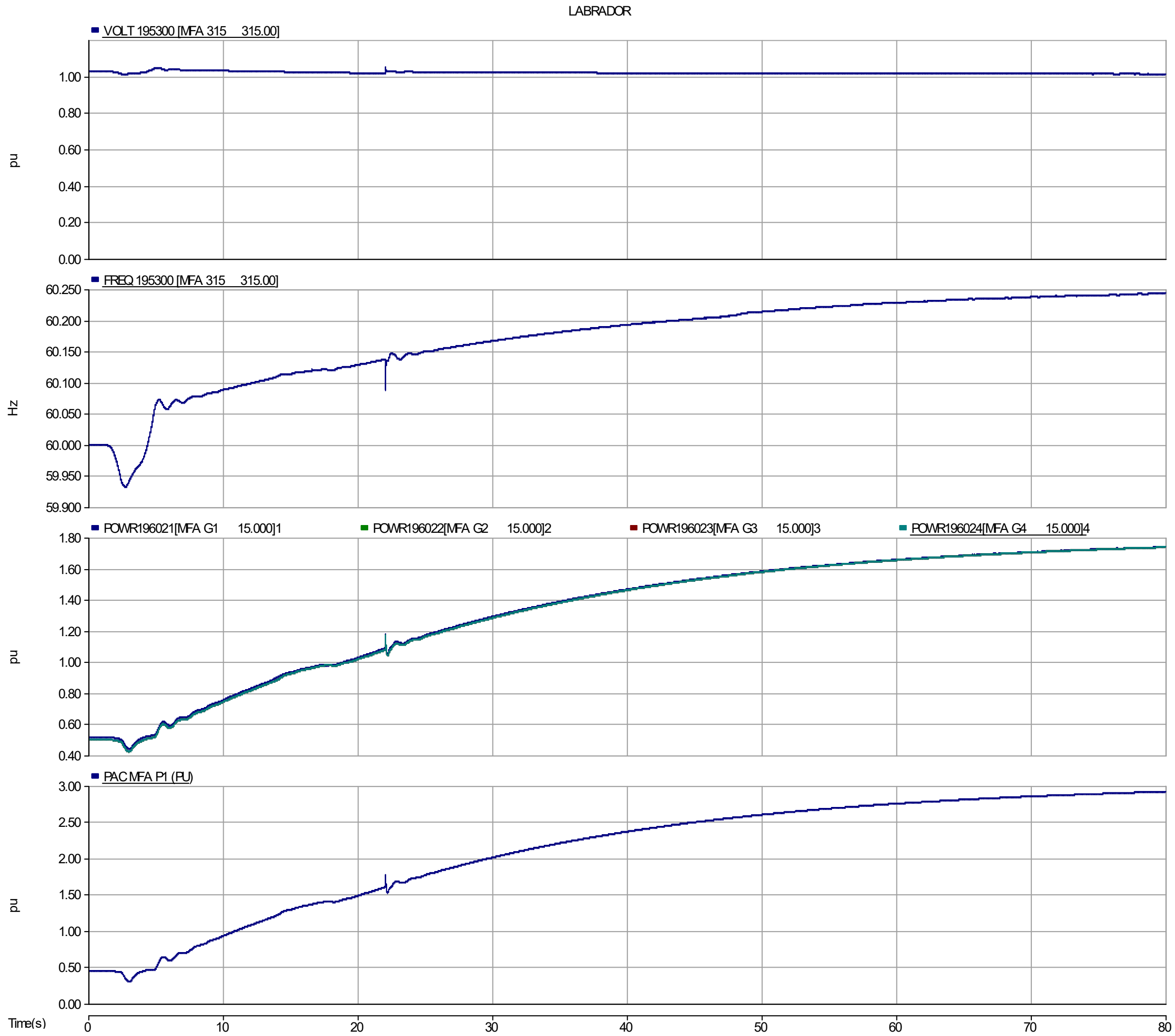

Figure 7-6. MFA generation ramped up to 700 MW (175 MW per generator)

7.2.5 Summary of Procedure

The following steps summarize the procedure simulated in this study:

- Place the first MFA unit on-line
- Energize the lines/transformers to Happy Valley (HVY) load bus
- Switch in a maximum block of 14 MW of HVY load
- Switch in a maximum block of 24 MW of HVY load

- Place the second MFA unit on-line
- Switch in a maximum block of 24 MW of HVY load
- Switch in a maximum block of 28 MW of HVY load
- Place the third MFA unit on-line
- Switch in the rest of the HVY load (10 MW to bring it up to 100 MW – peak load)
- Place the fourth MFA unit on-line
- Switch in the first MFA filter
- Switch in the second MFA filter
- De-block LIL pole 1 at 45 MW
- De-block LIL pole 2 at 45 MW
- Ramp up the MFA generators to a maximum of 175 MW per unit for isolated mode of operation

8. MFA Unit Out-of-Step Settings

It is noted that the results of transient stability studies have not indicated a requirement for out of step protection and that typically such protections are required for generators with high synchronous impedances that are connected to networks at voltages at 500 kV or greater. On this basis, out of step protection is not a requirement for Muskrat Falls units.

If an out of step protection scheme is to be implemented, the maximum angle difference between the MFA generator internal angle and the MFA generator terminal bus angle was determined.

In order to determine the largest angle difference that would take place from a normal disturbance on the Labrador system, the following disturbances were simulated:

- Normally cleared (100 ms) 3PF on MFA generator
- Normally cleared (100 ms) 3PF on L3101
- SPAR with successful reclose on L3101
- SPAR with unsuccessful reclose on L3101
- Loss of LIL bipole

The disturbances were tested with one, two, three and four MFA units in-service, with the units operating at 103 MW and 206 MW. Scenarios with the LIL out-of-service and with the LIL in-service at maximum power transfer were also tested.

The largest angle difference occurred during a 3PF at MFA on one of the MFA units, when the LIL was out-of-service and there were two fully loaded MFA units on-line prior to the fault. This case resulted in a maximum angle difference 60.5 degrees as shown in Figure 8-1.

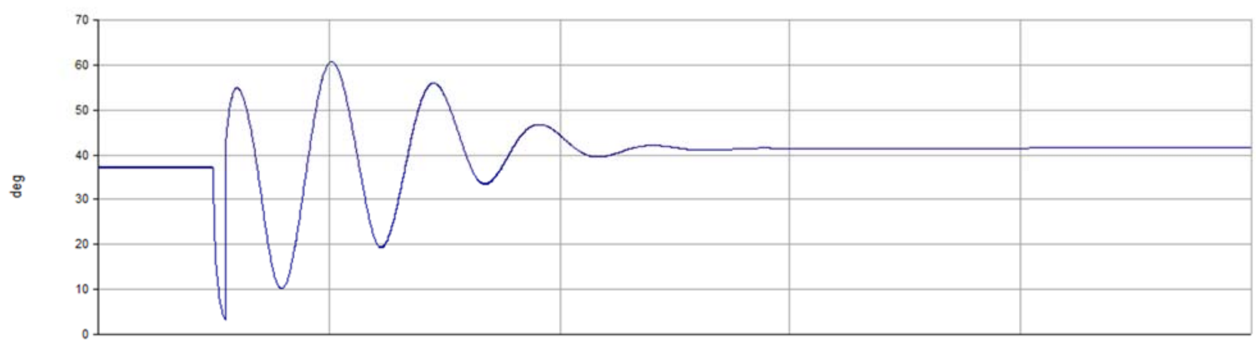

Figure 8-1. Largest angle difference of MFA generating unit

9. Conclusions

9.1 LIL Transfer Limits

LIL power transfer limits are required to ensure the (n-1) steady state voltage at Muskrat Falls remains within Transmission Planning Criteria limits of 0.9 pu to 1.1 pu over the full range of Labrador operating conditions. The determining contingency for overvoltage is either loss of the 150 MVAr reactor (if it is in-service) or loss of an MFA unit. The determining contingency for undervoltage is loss of one of the two 315 kV lines between Muskrat Falls and Churchill Falls.

This study analyzed scenarios with one, two, three and four MFA generating units in-service with the objective of determining the **minimum LIL transfer limits to avoid overvoltage conditions** on the Muskrat Falls 315kV bus (Section 3), and the **maximum LIL transfer limits to avoid undervoltage conditions** on the Muskrat Falls 315kV bus (Section 4).

The 150 MVAr reactor that is currently in-service at Muskrat Falls is assumed to be available during the early stages of the project as MFA units are brought online. This study determined that the reactor is required with one MFA unit on-line but can be removed from service once two MFA units are on-line, although it aids in preventing overvoltages with two MFA units on-line. It is not required when 3 or 4 MFA units are on-line. Table 9-1 summarizes these requirements.

Table 9-1. Need for 150 MVAr Reactor

Number of MFA Units On-line	Reactor Required?	Notes
1	**YES**	In addition to reactor, minimum LIL transfer limits as defined in Table 9-2.
2	**NO**, but useful	If reactor is not in-service, minimum LIL transfer limits as defined in Table 9-2.
3	**NO**	No overvoltage concerns
4	**NO**	No overvoltage concerns

The minimum and maximum LIL power transfer limits, summarized in Table 9-2, are dependent on how many MFA units are on-line, and on how much power the MFA units are generating[11].

Please note the following with regards to Table 9-2:

- Red text means that the maximum LIL power transfer limit is less than the next filter switch-in point, therefore there is a zone in which the LIL should not operate due to chance of voltage collapse if one of the 315 kV lines is out of service.

[11] The reactive power capability of the MFA units is highly dependent on the real power generation, which has a significant impact on the overvoltages and to moderate impact on the undervoltagess at Muskrat Falls.

- Blue text means that the minimum LIL power transfer limit is higher than the filter switch-out point for that number of filters (or higher than minimum LIL power at deblock), therefore there is a zone in which the LIL should not operate due to chance of overvoltage if the reactor or an MFA unit trip.
- Green text refers to the rated LIL power transfer levels associated with filter switch-in and switch-out points, i.e. normal operation.

Table 9-2. LIL Power Transfer Limits

Number of MFA Units	Status of Reactor	Number of Filters	To avoid overvoltages		To avoid undervoltages
			MFA Output (MW)	Minimum LIL Transfer Limit (Bipole) (MW)	Maximum LIL Transfer Limit (Bipole) (MW)
1	IN	2	103-195	90	280-300*
			195-206	150	
		3	103-180	270	340-360*
			180-206	345	
		4	103-206	540	420
2	IN	2	206-412	90	315
		3		270	540
		4		540	590-620*
	OUT	2	206-380	90	315
			380-412	150	
		3	206-370	270	585
			370-412	360	
		4	206-412	540	675-730*
3	OUT	2	309-618	90	315
		3		270	585
		4		540	815-900*
4	OUT	2	412-824	90	315
		3		270	585
		4		540	900

*Maximum LIL transfer limit range over the full range of MFA generation. Please refer to Section 4 for specific details.

9.2 315 kV Power Transfer Limits

9.2.1 System Intact

9.2.1.1 Direction - Churchill Falls to Muskrat Falls

The highest power transfer in the direction from Churchill Falls to Muskrat Falls occurs during high LIL power transfer and Happy Valley load conditions. The 315 kV power transfer is also highest when MFA generation is low. The LIL power transfer limits discussed and defined in Table 9-2 are associated with varying operating points that consider the full range of MFA generation from minimum to maximum. For further details regarding the specific operating points associated with these LIL power transfer limits, including the corresponding Churchill Falls to Muskrat Falls 315 kV power transfers, please refer to Section 4.

Please note that the Churchill Falls to Muskrat Falls 315 kV power transfers reported in Section 4 are not necessarily limits themselves, but are the corresponding power transfers associated with the operating point that defines the LIL power transfer limits.

9.2.1.2 Direction – Muskrat Falls to Churchill Falls

Table 9-3 summarizes the power transfer limits in the direction from Muskrat Falls to Churchill Falls under system intact conditions when the LIL is out-of-service or operating at minimum power.

Purple-highlighted limits are required to prevent system instability if there is a three-phase fault (3PF) on one of the two 315 kV CHF-MFA lines.

Table 9-3. System intact power transfer limits on MFA-CHF 315 kV corridor

MFA Units	MFA Gen (MW)	LIL (MW)	Power Flow (MW) – MFA to CHF		
			at CHF 735 kV	at CHF 315 kV	at MFA 315 kV
4	700	0	653	654	675
3	618 (max)	0	575*	577*	593*
2	412 (max)	0	380*	381*	387*
1	206 (max)	0	179*	180*	182*
4	700	45 (min)	611	612	630
3	618 (max)	45 (min)	533*	534*	548*
2	412 (max)	45 (min)	336*	337*	342*
1	206 (max)	45 (min)	135*	137*	167*

*Maximum possible power flow with 3,2,1 MFA generators on-line. This power transfer is not at a limit.

The following additional conclusions apply for the power transfer direction from MFA to CHF:

- It is recommended to use the tuned PSS parameters identified in this study for the MFA generators. Without these tuned parameters, a poorly damped oscillation occurs under high MFA to CHF power transfer with four MFA generators on-line when there is a 3PF on L3101 or L3102.
- As opposed to limiting MFA to CHF power when all four MFA generators are on-line as shown in Table 9-3, a stable system response shall be obtained by cross-tripping the fourth MFA generator in the event that L3101 or L3102 trips. This will allow for the transfer of 824 MW

from MFA to CHF, the entire output of the Muskrat Falls Generation Station. This solution still requires the tuned PSS parameters for the MFA generators to prevent a poorly damped oscillations.

9.2.2 Prior Outage L3101/L3102

If there is a prior outage of one of the two 315 kV CHF-MFA lines and the other line trips, the LIL will become isolated with the MFA generating units and Happy Valley load.

In order to maintain acceptable frequencies, Table 9-4 summarizes the CHF to MFA and MFA to CHF power transfer limits when there is a prior outage of either L3101 or L3102.

Table 9-4. Prior outage power transfer limits on CHF-MFA 315 kV corridor

MFA Units	CHF-MFA			MFA - CHF		
	MFA Gen (MW)	LIL* (MW)	315kV Power Transfer[12] (@ MF) (MW)	MFA Gen (MW)	LIL* (MW)	315kV Power Transfer[13] (@ MF) (MW)
4	700	794	120	700	628	94
3	525	590	91	525	430	70
2	350	390	65	350	275	50
1	175	180	30	175	125	26

*for a 15 MW Happy Valley Load

The following additional conclusions apply when there is a prior outage of L3101 or L3102:

- In order for the frequency response of the resulting isolated MFA system to be stable following the loss of the second CHF-MFA 315 kV line, the "isolated mode" parameters of the WSHYDD governor model[14] need to be in place. It is recommended that this mode switch be triggered within the digital governor if the frequency excursion is beyond a +/- 0.5 Hz deadband.
- It is recommended that governor tuning be performed during commissioning to ensure that oscillations are sufficiently damped during islanded conditions.

9.2.3 MFA Generators Isolated with LIL

If both of the 315 kV lines between CHF and MFA are out-of-service, the MFA generators are isolated with the LIL and Happy Valley load. The following conclusions apply to this mode of operation:

- **If MFA units controlling frequency**
  If the MFA units are relied upon to control the isolated system frequency (droop = 5%), the units should be kept to their minimum loading of 103 MW. If operating at more than minimum loading, and there is a 3PF on an MFA generating unit and the unit trips, a sustained oscillation

[12] Frequency dips to minimum of 58 Hz when the second 315 kV MFA-CHF line is lost.
[13] Frequency rises to maximum of 64 Hz (limit to ensure equipment protection not triggered) when the second 315 kV MFA-CHF line is lost.
[14] Andritz report "Governor Mathematical Model & Setting Parameters", MFA-AH-SD-3411-EL-H46-0001-01, 11 May 2018 lists the recommended "isolated mode" parameters. This study determined that a better response can be obtained by changing K1 from 5.63 to 8.

can occur in the MFA governor response of the remaining units, frequency dips below 58 Hz and the system can go unstable.

- **If LIL rectifier put into frequency control (recommended)**
  It is recommended to place the LIL in frequency control at the MFA terminal. The frequency controller will respond to loss of an MFA unit by reducing LIL power transfer. To avoid UFLS on the IIS following the reduction of LIL power infeed, the LIL frequency controller at the MFA terminal should be limited to a maximum of 120 MW. Under these operating conditions with the LIL frequency controller in-service at MFA, the maximum MFA unit loading is listed in Table 9-5. These limits are required to keep the isolated system frequency above 58 Hz and to avoid sustained oscillations in MFA governor response in case an MFA unit trips.

Table 9-5. MFA unit limits in isolated mode with LIL frequency control at MFA

# of MFA Units	Power limit of each MFA unit (MW)	LIL Power Transfer* (MW)
4	185	720
3	140	395
2	135	240
1	144*	120

*for a 15 MW Happy Valley Load. LIL power transfer would be less with higher Happy Valley load

When enabling the LIL frequency controller at MFA, the frequency controller that is normally enabled at the SOP terminal of the LIL should be disabled.

9.3 Labrador System Restoration

Two simple system restoration procedures were presented in Section 7:

- Option 1 - To restore the MFA 315 kV bus from Churchill Falls
- Option 2 - To restore the MFA units, the LIL and the Happy Valley load as an isolated system

9.4 Out-of-Step Protection for MFA units

It is noted that the results of transient stability studies have not indicated a requirement for out of step protection and that typically such protections are required for generators with high synchronous impedances that are connected to networks at voltages at 500 kV or greater. On this basis, out of step protection is not a requirement for Muskrat Falls units. The study found the largest angle difference between the MFA generator internal angle and the MFA generator terminal bus angle was 60.5 degrees.

Appendix 1

MFA - WHSYDD Parameters

Muskrat Falls Generators: WSHYDD

Parameter	Muskrat Falls 1,2,3,4	
	Normal Mode	Isolated Mode
Db1	0	0
Err	0	0
Td (sec)	0.08	0.08
Ki	2.0	8.0
Tf (sec)	0.08	0.08
K2	0	1.56
K1	3.0	0.32
R	0.05	0.05
Tt	0.3	0.3
Kg	1.0	1.0
Tp (sec)	0.3	0.3
VELopen (>0)	0.125	0.125
VELclose (>0)	0.125	0.125
Pmax	1.0	1.0
Pmin	0.0	0.0
Db2	0.0	0.0
GV1	0.1	0.1
Pgv1	0.0	0.0
GV2	0.1734	0.1734
Pgv2	0.2273	0.2273
GV3	0.462	0.462
Pgv3	0.4659	0.4659
GV4	0.4876	0.7846
Pgv4	0.5114	0.5114
GV5	0.8585	0.8585
Pgv5	1.0	1.0
Aturb	-1.0	-1.0
Bturb (>0)	0.5	0.5
Tturb (>0) (sec)	1.86	1.86
Trate	209.24	209.24

Appendix 2

MFA – Recommended PSS Parameters

Muskrat Falls Generators: PSS2B

Parameter	Muskrat Falls 1,2,3,4
TW1 Washout Time constant - Signal 1	10
TW2 Washout Time Constant - Signal 1	10
T6 Lag Time Constant - Signal 1	0.05
TW3 Washout Time Constant - Signal 2	10
TW4 Washout Time Constant - Signal 2	0
T7 Lag Time Constant - Signal 2	10
KS2 Gain - Signal 2	1.2195
KS3 Gain - Signal 2	1
T8 Ramp Tracking Filter Lead Time Constant	0.5
T9 Ramp Tracking Filter Lag Time Constant	0.1
KS1 Stabilizer Gain	15
T1 Lead Time Constant - Phase Comp. Block 1	0.299
T2 Lag Time Constant - Phase Comp. Block 1	0.0814
T3 Lead Time Constant - Phase Comp. Block 2	0
T4 Lag Time Constant - Phase Comp. Block 2	0
T10 Lead Time Constant - Phase Comp. Block 3	0
T11 Lag Time Constant - Phase Comp. Block 3	0
VS11MAX Stabilizer Input Maximum. Input 1	0.1
VS11MIN Stabilizer Input Minimum. Input 1	-0.1
VS12MAX Stabilizer Input Maximum. Input 2	1.1
VS12MIN Stabilizer Input Minimum. Input 2	0
VSTMAX Stabilizer Output Maximum	0.1
VSTMIN Stabilizer Output Minimum	-0.1

Engineering Support Services for:

RFI Studies

Newfoundland and Labrador Hydro

Attention: Mr. Rob Collett

Stage 4D LIL Bipole: Transition to High Power Operation

Technical Note: TN1205.71.04
Date of issue: September 25, 2019

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Table of Contents

1. Executive Summary

Operational studies are underway to determine the system operating limits of the Newfoundland and Labrador Hydro (Hydro) Island Interconnected System (IIS). To date, several stages of operational studies have been performed to identify Labrador Island link (LIL) and Maritime Link (ML) transfer limits for the phased monopolar approach, with the LIL monopole operating up to a maximum of 225 MW.

Stage 4 is the final stage of operational studies and includes the 900 MW LIL bipole, the Muskrat Falls (MFA) generators, the Soldiers Pond (SOP) synchronous condensers and the ML. The Holyrood thermal generators (HRD), the Stephenville Gas Turbine, and the Hardwoods Gas Turbine are no longer in-service[1]. Holyrood Unit 3 is operating as a synchronous condenser. To date, several preliminary Stage 4 operational studies looking at key issues at high power operation with all equipment and LIL bipole functionality in-service have been performed.

As of today, the system is operating as follows:

- ML and its frequency controller[2] in-service, with operating limits as per operational studies
- LIL monopole in-service (225 MW), with operating limits as per operational studies
- 2x75 MVAR filters at SOP
- 1x72 MVAR filter at MFA, 1x150 MVAR reactor at MFA
- 0 to 3 HRD units in-service as required
- No SOP synchronous condensers in-service
- No MFA units in-service

This report investigates the period in time where the system is transitioning from low to high power operation on the LIL. LIL and ML transfer limits are determined for this period in time as more equipment comes in to service.

As equipment is being brought online, the following considerations/sensitivities are considered in this report:

- Number of SOP synchronous condensers in-service (1 or 2)
- LIL operating as monopole or bipole
    - Without frequency control
    - Without 2 pu 10-minute overload capability for loss of a pole
- Number of SOP and MFA filters (needed to meet IEC harmonic distortion limits)

[1] The Stephenville Gas Turbine and the Hardwoods Gas Turbine are scheduled to be retired in in the early 2020's. This study considers long term operation after these units are no longer in service.
[2] Assumes ML frequency controller can provide up to 150 MW from Nova Scotia to Newfoundland, and up to 60 MW from Newfoundland to Nova Scotia

1.1 LIL Transfer Limits

The contingencies that define the LIL transfer limits are loss of the LIL bipole and loss of a LIL pole. LIL transfer limits for the transitional period are shown in Figure 1–1 (ML frequency controller in-service) and Figure 1–2 (ML frequency controller out-of-service).

Loss of the LIL Bipole
Ultimately, the Underfrequency Load Shed (UFLS) scheme will be modified/re-designed to ensure that the system remains stable and that the IIS frequency remains above 58 Hz following the loss of the LIL bipole, as per Transmission Planning Criteria. However, during the period when the system is transitioning from low to high power operation, the existing UFLS scheme will remain in place, therefore LIL transfer limits are needed to ensure that the system remains stable following the loss of the LIL bipole. The frequency criteria used in this study allowed the 58 Hz block of load to be shed if the LIL bipole is lost, as long as the system recovered well and in a stable manner following the loss of LIL bipole. Note also that if the LIL bipole is lost, the ML (if exporting) will runback[3].

Loss of the LIL Pole
Transmission Planning Criteria for loss of a LIL pole states that this event should not cause the IIS frequency to drop below 59 Hz, and it should not result in UFLS. The LIL will ultimately have a 10-minute 2 pu overload rating to allow operators time to quickly turn on generation if a LIL pole is lost. However, during the period when the system is transitioning from low to high power operation, this overload capability will not be available, therefore LIL power transfer limits are needed to ensure that frequency does not drop below 59 Hz for loss of a LIL pole. Additionally, ML runback can be used to keep frequency above 59 Hz for certain cases when a LIL pole is lost.

[3] If the ML is not exporting, the ML response would be limited to frequency controller action.

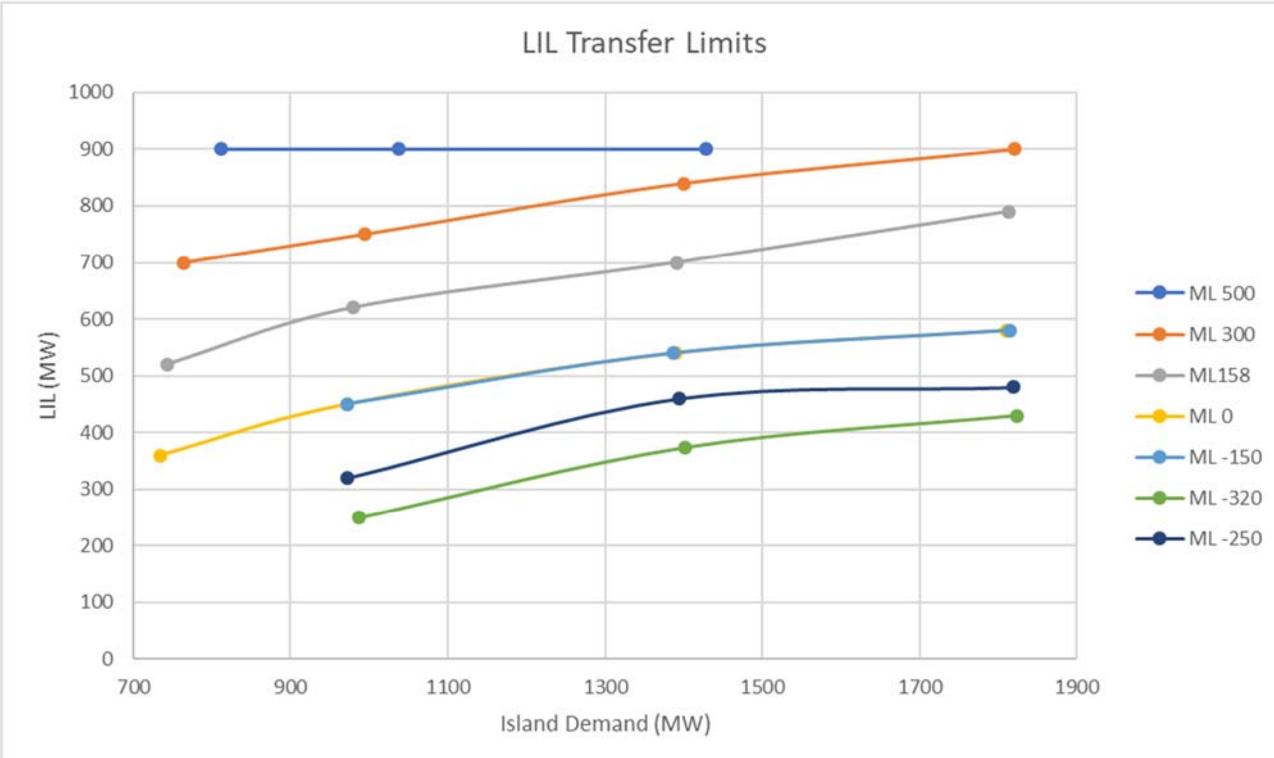

Figure 1–1. LIL Transfer Limits (ML Frequency Controller in-service)

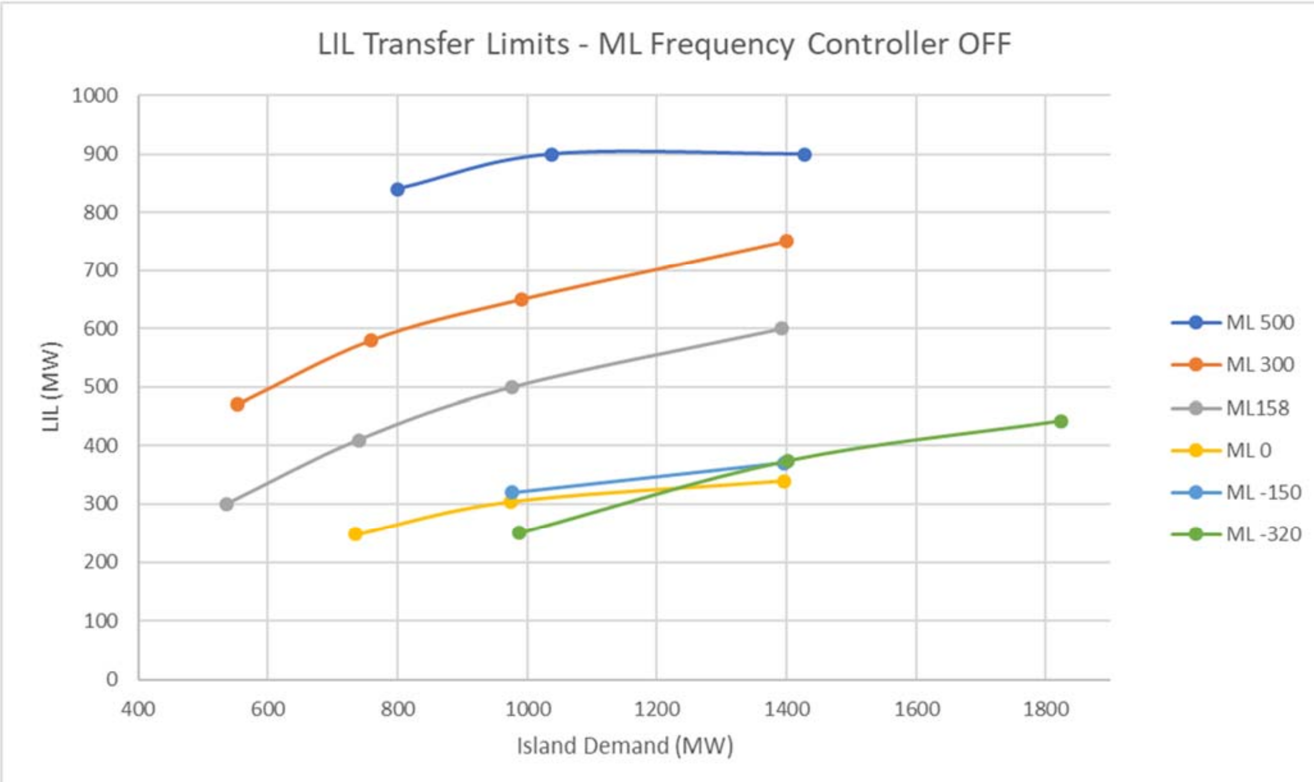

Figure 1–2. LIL Transfer Limits (ML Frequency Controller out-of-service)[4]

1.2 ML Transfer Limits

As per Transmission Planning Criteria, loss of an ML pole (when importing) should not result in UFLS and frequency should remain above 59 Hz. UFLS is allowed for loss of the ML bipole, however the frequency should remain above 58 Hz. If exporting, frequency should remain below 62 Hz for loss of an ML pole or bipole.

1.2.1 Without use of LIL Runbacks or Run-ups

ML transfer limits without the use of LIL runbacks or run-ups are show in Figure 1–3. This figure assumes that no HRD units are in-service during ML export. Figure 1–4 depicts the ML export limits[5] with 1, 2 and 3 HRD units in-service.

[4] Without the ML frequency controller in service, LIL transfers must be limited in peak load conditions as explained in Section 3.2 and listed in Table 3.2. These operating points are therefore excluded from the plot.
[5] More restrictive ML export limits are needed when HRD units are in-service in order to limit the decrease in power output to 15 MW per HRD unit in response to the system overfrequency that occurs when the ML bipole is lost.

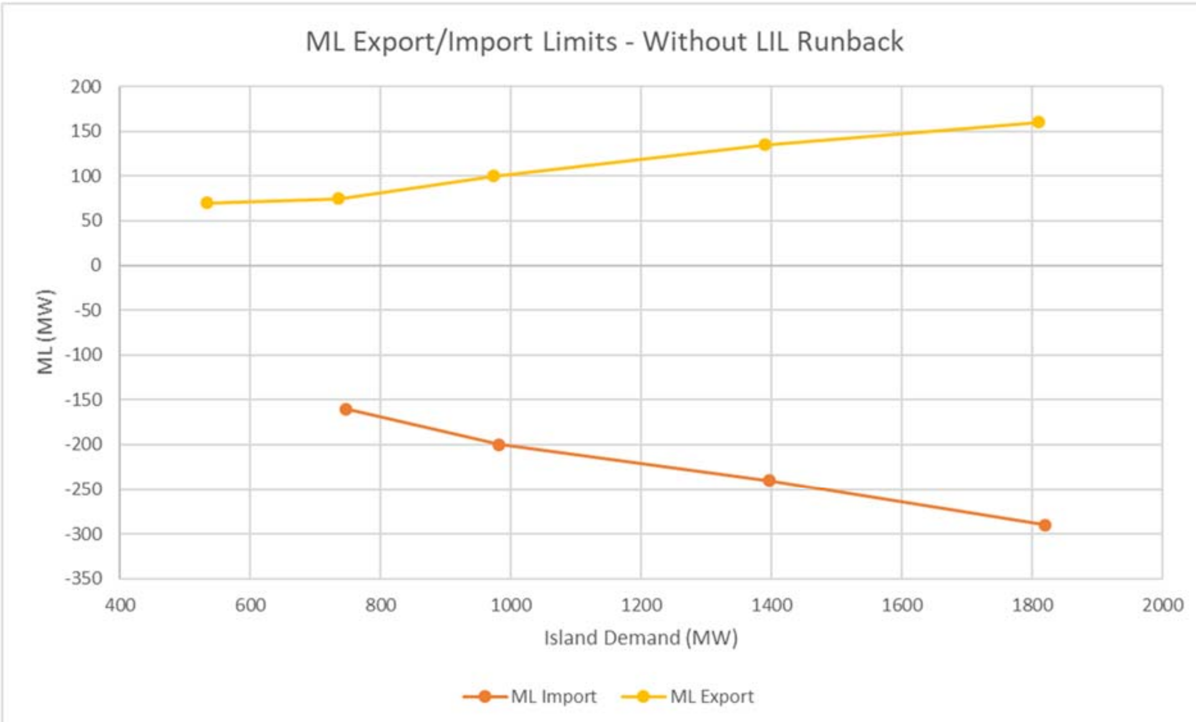

Figure 1–3. ML import/export limits, without LIL run-ups/runbacks or frequency control

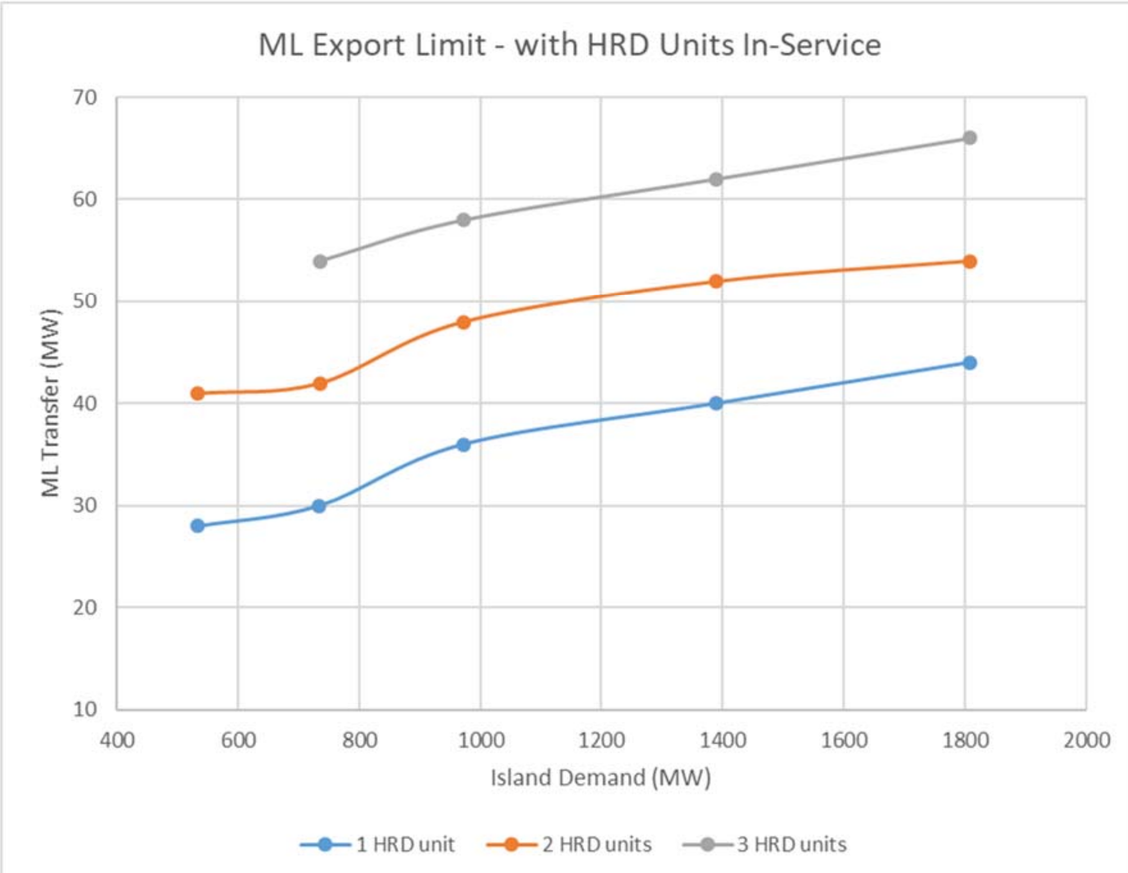

Figure 1–4. ML Export Limits with HRD Units In-service (without LIL runbacks)

1.2.2 With the use of LIL Runbacks and Run-ups

If LIL run-ups are initiated when there is loss of ML import, and LIL runbacks are initiated when there is loss of ML export, then ML power transfer is not limited, and the ML can operate over its full range from 320 MW import to 500 MW export. This assumes that there is sufficient room available on the LIL (up or down) to cover for loss of the ML bipole.

A simple approach to determine the amount of LIL runback or run-up that is required for a particular ML import or export level is to simply runback or run-up the LIL by the amount of ML export or import that was lost. Note that the LIL runback or run-up should be high enough at MFA to consider LIL losses such that the total LIL runback or run-up as measured at Soldiers Pond is equal to the amount of ML export or import that was lost. This method is applicable to all levels of ML import or export over all ranges of IIS demand.

1.3 Additional Conclusions

The following additional conclusions were made during the study.

1. **Need for Avalon Generation during High Island Demand**
   The IIS can become unstable if the LIL bipole trips during high IIS demand. It was determined that a

minimum amount of Avalon generation (as defined in Table 1-1) is required to be in-service when IIS demand is greater than 1600 MW to prevent system instability if the LIL bipole is lost. The Come-By-Chance capacitor banks should also be in-service (as many as steady state voltage allows) when the power flow eastward from Bay d'Espoir (BDE) towards SOP is high to help support the voltage if the LIL bipole is lost. Note, however, that despite these mitigation measures, a 0.7 Hz oscillation in the voltage and violations of transient voltage criteria along the Bay d'Espoir to Soldiers Pond corridor were still observed in peak demand cases with high BDE to SOP power flow if the LIL bipole trips. Further investigation is required to see if the voltage response can be improved.

Table 1-1. Minimum Avalon Thermal Generation Required to be in-service

IIS Demand (MW)	Avalon Generation (MW)
1700 - 1830	90-100
1650-1700	60-70
1600-1650	30

Additionally, in line with previous operational studies[6], when power flow from BDE to SOP reaches levels around 650 MW (with or without the LIL in service), the IIS can also experience instability if there is a three phase fault (3PF) on line TL267. Therefore, power flow on this corridor should be limited to 650 MW during this transitional period from low to high power.

2. **Impact of SOP Synchronous Condensers on LIL Transfer Limits**
The SOP synchronous condensers provide inertia to the Island, and they help the system by slowing down the rate of change of frequency immediately after infeed from the LIL is lost. It was found that although they slow down the initial rate of change of frequency, they do not impact the minimum frequency that occurs, and therefore the transfer limits defined in this study were the same whether one or two SOP synchronous condensers were in-service.

3. **Concept of "Net DC"**
The concept of "Net DC" to the IIS applies when the ML is exporting and can be runback to 0 MW if the LIL bipole is lost. For example, at a 1400 MW demand level, LIL power transfer is limited to 810 MW if ML is exporting 300 MW. At the same demand level, LIL power transfer is limited to 700 MW if ML is exporting 158 MW and to 540 MW is ML is operating at 0 MW. In all of these cases, subtracting ML export from the LIL transfer limit results in a value of around 540 MW, which could be termed the "Net DC" limit. Figure 1–5 shows the approximate "Net DC" limits when the ML is exporting. Note that the "Net DC" limits are very similar for various ML export levels.

[6] TGS report R1529.01.02 "Solutions to Serve Island Demand during a LIL Bipole Outage", and TGS report TN1205.62.05 "Stage 4A LIL Bipole: Preliminary Assessment of High Power Operation".

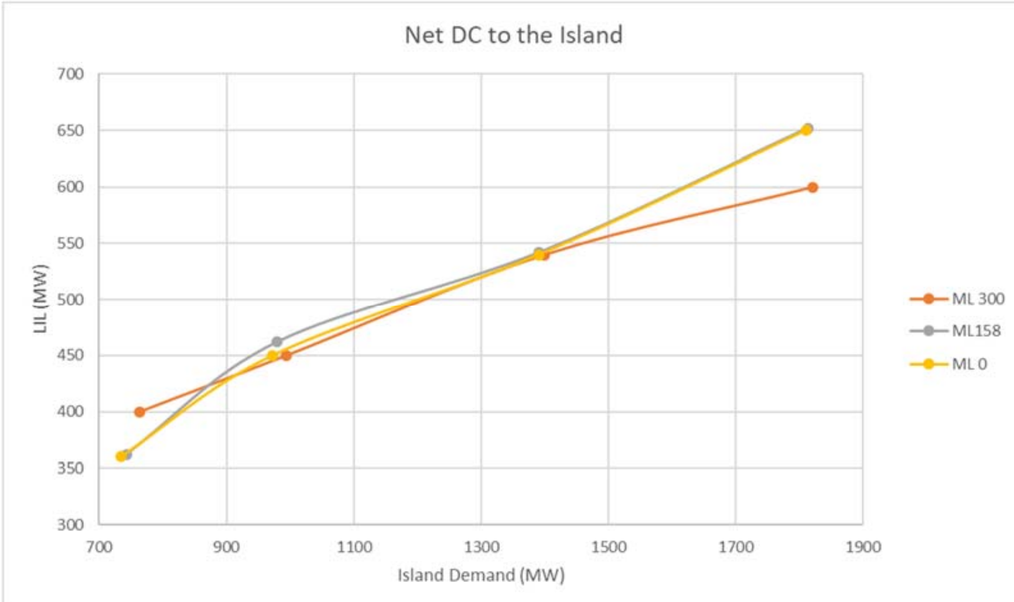

Figure 1–5. Maximum "Net DC" to the Island during ML export

1.4 Harmonic Analysis

In order to meet IEC harmonic limits, the analysis concluded that the LIL may be operated up to 675 MW in monopole operation and 900 MW in bipole operation with the filter configurations listed in Table 1-2.

Table 1-2. LIL limits and filter configurations to meet IEC harmonic limits

Monopole Operation up to 675 MW		Bipole Operation up to 900 MW	
Muskrat Falls	**Soldiers Pond**	**Muskrat Falls**	**Soldier's Pond**
two A type	one A type, one B type	two A type filters**	one A type, one B type
two A type, one B type	one A type, two B type	two A type, one B type	one A type, two B type
two A type, two B type	two A type, two B type	two A type, two B type	two A type, two B type
three A type, one B type	two A type, three B type	three A type, one B type	two A type, three B type
	three A type, two B type		three A type, two B type

** except when only one or two MFA units are in service under light load conditions, or when only one MFA unit is in service under peak load conditions, in which case, operation is possible only up to 810 MW with two A type filters

2. Study Models and Criteria

The Interconnected Island System (IIS) is the area of focus for this study.

2.1 Interconnected Island System

The 230 kV network of the IIS is shown in Figure 2–1.

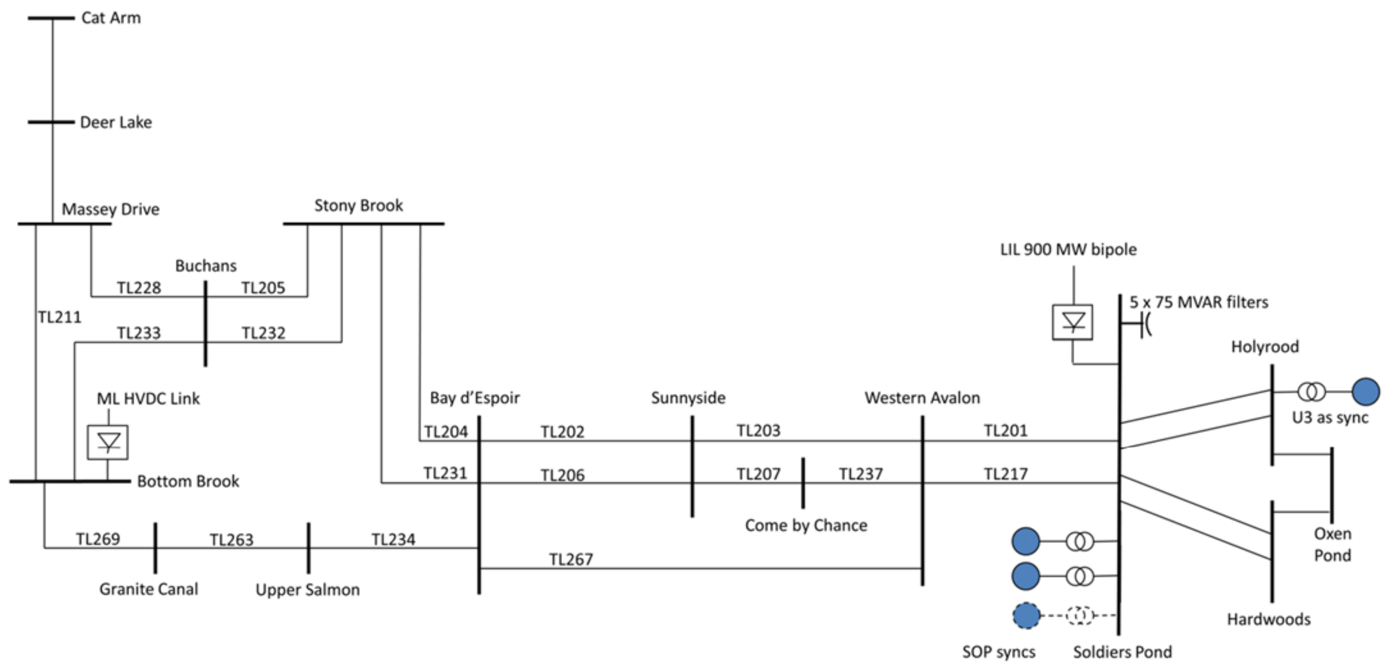

Figure 2–1. Interconnected Island System 230 kV grid

2.2 Study Assumptions

The following assumptions are made for this study:

- HRD units (1,2,3) are available as required, until the full LIL 900 MW bipole and all associated equipment and LIL control functionality are in-service.[7] The final Stage 4 operational study will assume that the HRD units have been retired.
- LIL frequency controller is not in-service. The LIL frequency controller will be considered in-service in the final Stage 4 operational study.
- LIL 2 pu 10-minute overload is not available.
- The existing ULFS scheme will remain as is. The new UFLS scheme will be assumed in-service in the final Stage 4 operational study.

[7] Thermal generation is minimized in all base cases, but may be increased, as required, if transmission system violations are found.

- ML can operate between 320 MW import and 500 MW export, if not limited by operational restrictions
- As long as import capacity is available, the ML frequency controller will provide up to 150 MW of frequency support if a LIL pole or the bipole is lost or for other underfrequency events that cause the ML frequency controller to operate

2.3 Study Criteria

The applicable Transmission Planning Criteria for this study is summarized below:

- Steady state voltage : 0.95 pu – 1.05 pu during n-0 conditions
- Steady state voltage : 0.90 pu – 1.1 pu during n-1 conditions
- Post fault recovery voltages on the ac system shall be as follows:
    - Transient undervoltages following fault clearing should not drop below 70%
    - The duration of the voltage below 80% following fault clearing should not exceed 20 cycles
- Post fault system frequencies shall not drop below 59 Hz and shall not rise above 62 Hz
- For a permanent loss of the ML bipole, underfrequency load shedding shall be permitted, but controlled, and the system frequency shall not drop below 58 Hz
- For a permanent loss of the LIL bipole, underfrequency load shedding is permitted, but controlled, and the system frequency is allowed to shed the 58 Hz block of load shed, as long as the system recovers in a stable manner. This criteria is only valid during the transition phase from low to high power operation.

2.4 Contingencies

Table 2-1 lists the contingencies that were considered in this study.

Table 2-1. Contingencies

Line/Generator	Description
Loss of LIL pole	Permanent loss of LIL pole. Assume no 2pu overload functionality
Loss of LIL bipole	Permanent loss of LIL bipole
Loss of ML bipole	Permanent loss of ML bipole
Loss of ML bipole	Permanent loss of ML pole

2.5 PSSE Base Cases

Table 2-2 lists the base cases that were used to analyze the IIS system in this study.

Table 2-2. Base cases

Load Condition	Island Demand (MW)[8]	LIL Power Transfer (at MFA) (MW)	Island Generation (MW)
Peak[9]	1825	810 (import)	1214
Intermediate Peak	1391	700 (import)	889
Intermediate	980	620 (import)	548
Light	743	520 (import)	402
Extreme Light	537	300 (import)	402

[8] Island Demand includes load and losses. Variations in Island Demand for the same loading condition are attributed to incremental losses associated with variations in dispatch.
[9] Peak loading conditions are based on 2028 forecasted load.

3. LIL Transfer Limits

There are two contingencies that define the LIL transfer limits:

1. Loss of a LIL pole
2. Loss of the LIL bipole

Loss of the LIL Bipole

Loss of the LIL bipole is the contingency that defines the requirements of the UFLS scheme for the IIS. Ultimately, the UFLS scheme will be modified/re-designed during the final Stage 4 operational study to ensure that the system remains stable and the IIS frequency remains above 58 Hz following the loss of the LIL bipole, as per Transmission Planning Criteria.

This report is investigating the period in time where the system is transitioning from low to high power operation. During this time, the existing UFLS scheme will remain in place and that LIL transfer limits will be enforced as required to ensure that the system remains stable following the loss of the LIL bipole. The frequency criteria used in this study allowed the 58 Hz block of load to be shed if the LIL bipole is lost, as long as the system recovered well and in a stable manner following the loss of LIL bipole and the subsequent UFLS. Note also that if the LIL bipole is lost, the ML (if exporting) will be runback to 0 MW[10].

Loss of the LIL bipole was simulated for IIS system conditions ranging from extreme light to peak demand, and for levels of ML power transfer ranging from 300 MW import to 500 MW export. There are two stability issues that were observed when the LIL bipole is lost:

1. Decline in IIS frequency and subsequent UFLS
2. Voltage collapse around the mid-point of the BDE-SOP 230 kV corridor (around Sunnyside) during high IIS demand conditions

LIL transfer limits required for reasons of underfrequency are described in Section 3.1 and Section 3.2. The voltage collapse issue is discussed further in Section 3.3.3.

Loss of the LIL Pole

The Transmission Planning Criteria for loss of a LIL pole are specified such that this event should not cause the IIS frequency to drop below 59 Hz, and it should not result in UFLS.

The LIL is ultimately being designed with a 10-minute 2 pu overload rating. If one of the LIL poles is lost, the remaining pole is rated to transmit 2 pu for 10 minutes, after which the continuous monopole rating drops down to 1.5 pu. The purpose of the 10-minute 2.0 pu overload rating is to allow operators time to quickly turn on generation to make up for the loss of infeed from the LIL pole that was lost.

During the transition from low to high power operation, this 2 pu overload capability will not yet be available. Instead, LIL power transfer limits must be enforced to ensure that the IIS frequency does not drop below 59 Hz for loss of a LIL pole. Note that if a LIL pole is lost, it is assumed that the healthy LIL pole will pick up the transfer that was lost on the other LIL pole, up to its rating of 450 MW.

[10] If the ML is not exporting, the ML response would be limited to frequency controller action.

As per the results presented in the following sections, the pole compensation process described above is restricted in some cases due to the limited firing angle range of the LIL. This limited range is such that converter transformer tapchanger operation may be required before full compensation can be achieved. Therefore there is a capacity shortfall in the seconds required for the tapchanger operation to occur. This may require ML frequency controller response, ML run back action or load limitation on the LIL to prevent underfrequency load shedding. This limitation in the firing angle is known by the vendor and will be assessed for a solution in future software revisions.

Loss of a LIL pole was simulated for the same IIS system conditions as the LIL bipole. The LIL transfer limits determined for loss of the LIL bipole were checked to ensure that loss of a LIL pole at these LIL power transfer limits would meet the 59 Hz criteria. The simulations showed that in order to keep the IIS frequency above 59 Hz, loss of a LIL pole requires a runback on the ML under certain operating conditions and, in some instances, requires more limiting LIL transfer levels than loss of the LIL bipole.

LIL transfer limits for loss of a LIL pole and bipole are discussed in Section 3.1 with the ML frequency controller in-service, and in Section 3.2 with the ML frequency controller out-of-service.

3.1 With ML Frequency Controller In-Service

In the majority of cases, LIL transfer limits are defined by loss of the LIL bipole. However, there are a few instances where loss of a LIL pole is more limiting than loss of the bipole, given that the 2 pu 10-minute overload rating is not available yet and UFLS must be avoided.

Table 3-1 summarizes the LIL transfer limits needed to maintain IIS system stability for loss of LIL bipole while allowing the 58 Hz block of load to be shed, and for loss of a LIL pole to maintain IIS frequency at or above 59 Hz. It also lists the ML runbacks assumed/needed for each case for scenarios when the ML is exporting. Please note the following:

- In all peak demand cases, voltage considerations were found to be more limiting than underfrequency concerns. The results in the table below only reflect underfrequency limits, while Section 3.3.3 discusses the voltage collapse issue and prevention in more detail.
- LIL transfer levels shown in green text are at maximum LIL rating of 900 MW, and the frequency response of the system is above the 58 Hz criteria.
- In all cases, LIL transfer limits were first determined for loss of the LIL bipole. This same transfer level was tested for loss of a LIL pole. If loss of a LIL pole resulted in frequency dropping below 59 Hz, the LIL transfer limit was reduced in order to keep frequency above 59 Hz for loss of a pole. LIL transfer levels shown in red text are instances where loss of a LIL pole is more limiting than loss of the LIL bipole.

Table 3-1. LIL Transfer Limits and ML Runbacks

ML (MW)	Demand (MW)	Generation (MW)	Loss of LIL Bipole			Loss of LIL Pole			
			LIL Transfer Limit (MW)	ML Runback (MW)	Min. Freq. (Hz)	LIL Transfer Limit (MW)	ML runback (MW) 100 ms delay	ML runback (MW) 500 ms delay	Min. Freq. (Hz)
500	1428**	1094	900*	500	58.37	900	260	284	59.0
	1038	703	900	500	58.25	900	250	360	59.0
	812	476	900	500	58.20	900	256	440	59.0
300	1821	1285	900*	300	57.90	900	264	270	59.0
	1400	915	840	300	57.94	840	224	260	59.0
	994	589	750	300	57.95	750	136	218	59.0
	764	404	700	300	57.99	700	96	130	59.0
158	1813	1214	810*	158	57.90	790	158	158	59.0
	1391	889	700	158	57.90	700	102	102	59.0
	980	548	620	158	57.97	620	38	32	59.0
	743	402	520	158	58.02	520	0	0	59.10
0	1811	1195	650*	-	57.88	596	-	-	59.0
	1390	872	540	-	57.90	540	-	-	59.08
	972	538	450	-	57.96	450	-	-	59.26
	734	384	360	-	57.98	360	-	-	59.32
-150	1815	1049	650*	-	57.95	564	-	-	59.0
	1387	720	540	-	57.93	540	-	-	59.01
	972	424	410	-	57.99	410	-	-	59.26
-250[11]	1826	1092	550	-	57.90	504	-	-	59.0
	1394	701	460	-	57.91	500	-	-	59.0
-320[12]	1824	998	500*	-	57.86	442	-	-	59.0
	1402	724	390	-	57.92	374	-	-	59.0
	987	421	250	-	57.99	250	-	-	59.2

*Unstable unless Avalon generation put in-service (see Section 3.3.3 for more detail)

**At maximum Island generation (with HRD off-line). For IIS demand > ~1400 MW, cannot export the full 500 MW on ML.

Figure 3–1 graphically depicts the most limiting LIL transfer limits from Table 3-1. Each line on the plot represents a different ML export or import level from 500 MW export to 320 MW import.

[11] Please note that ML frequency controller action is limited to provide 70 MW of support from Nova Scotia when already importing 250 MW.

[12] Please note that there is no MW support available from Nova Scotia when already importing 320 MW.

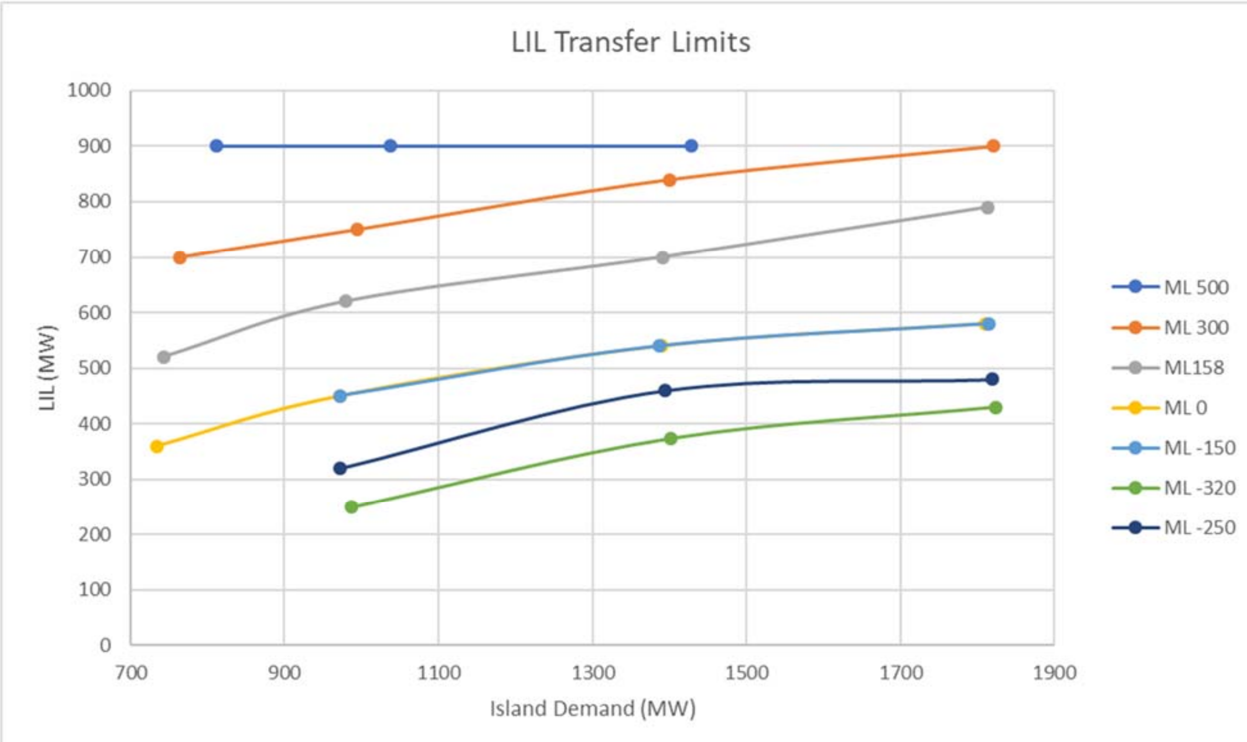

Figure 3–1. LIL Transfer Limits for varying ML import/export levels (ML Frequency Controller in-service)

3.2 Without ML Frequency Controller In-Service

If the ML frequency controller is not in service, LIL transfer is further limited because the 150 MW of capacity support is not available. Table 3-2 lists the LIL transfer limits resulting from loss of the LIL bipole and loss of a LIL pole with the ML frequency controller out-of-service. Following the table, Figure 3–2 graphically depicts the most limiting LIL transfer limits from Table 3-2. Each line on the plot represents the LIL transfer limit for a given ML transfer level ranging from ML import of 320 MW to ML export of 500 MW.

- In all of the peak demand cases, voltage considerations were found to be more limiting than underfrequency concerns. The results in the table below only reflect underfrequency limits. Section 3.4 discusses the voltage collapse issue and prevention in more detail.
- LIL transfer levels shown in red highlighted cells are cases where the IIS is at maximum generation and requires the LIL to be at the transfer limit shown in order to meet demand, however loss of a LIL pole at this transfer level results in a frequency dip below 59 Hz. These points are not included in Figure 3–2 because they result in UFLS for loss of a LIL pole.
- In all cases, LIL transfer limits were first determined for loss of the LIL bipole. This same transfer level was tested for loss of a LIL pole. If loss of a LIL pole resulted in frequency dropping below 59 Hz, the LIL transfer limit was reduced in order to keep frequency above 59 Hz for loss of a

pole. LIL transfer levels shown in red text are instances where loss of a LIL pole is more limiting than loss of the LIL bipole.

Table 3-2. LIL Transfer Limits with ML Frequency Controller Out-of-Service

ML (MW)	Demand (MW)	Generation (MW)	Loss of LIL Bipole			Loss of LIL Pole		
			LIL Transfer Limit (MW)	ML Runback (MW)	Min. Freq. (Hz)	LIL Transfer Limit (MW)	ML runback (MW)*	Min. Freq. (Hz)
500	1428	1094	900	500	57.98	900	414	59.0
	1038	703	900	500	57.89	900	398	59.0
	800	517	840	500	57.92	900	450	59.0
300	1821	1285	900	300	57.82	900	300	58.6
	1400	994	750	300	57.83	760	300	59.0
	991	674	650	300	57.90	750	300	59.0
	760	453	580	300	57.93	700	214	59.0
158	1813	1310	764	158	57.81	730	158	58.6
	1392	979	600	158	57.82	604	158	59.0
	977	654	500	158	57.89	610	158	59.0
0	1823	1324	540	-	57.80	540	-	58.6
	1397	991	420	-	57.83	340	-	59.08
	975	653	330	-	57.87	304	-	59.26
	736	492	248	-	57.89	336	-	59.32
-150	1826	1195	500	-	57.82	420	-	58.8
	1396	849	410	-	57.87	370	-	59.01
-320	1824	998	500	-	57.86	442	-	59.0
	1402	724	390	-	57.92	374	-	59.0

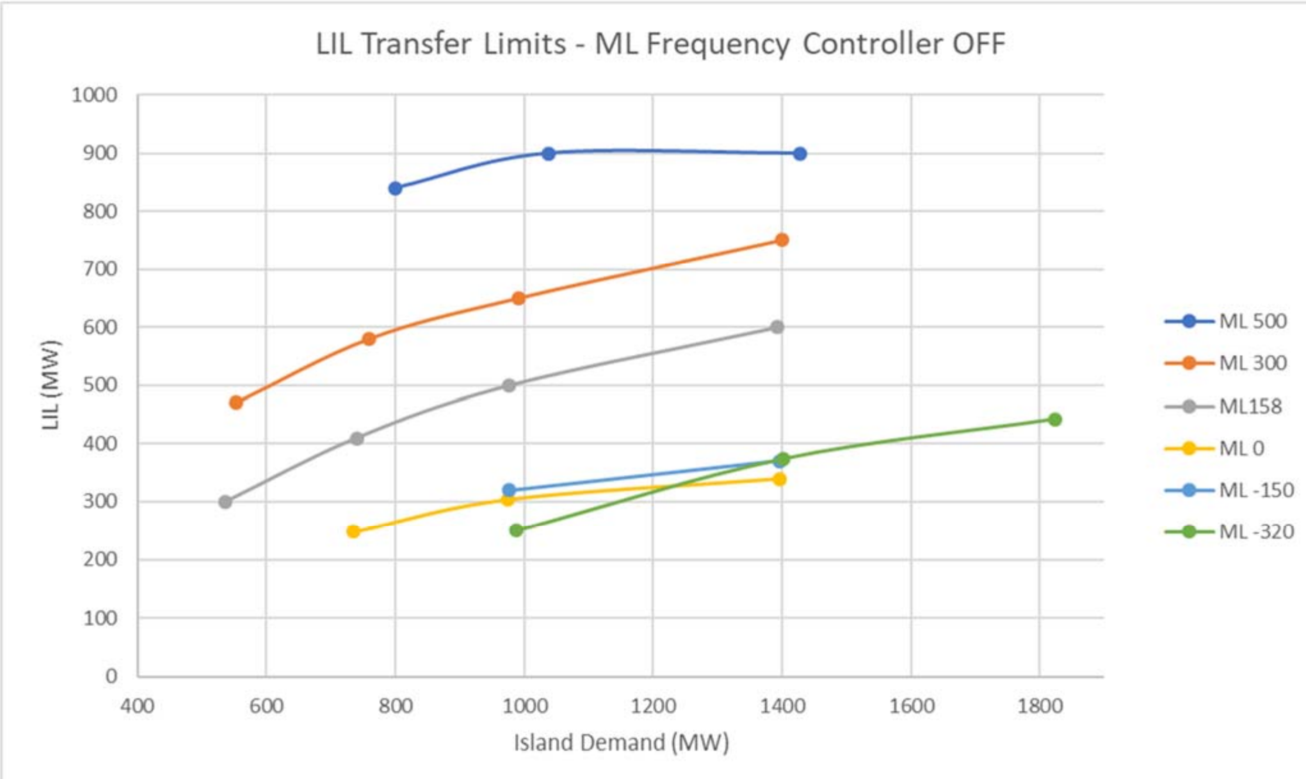

Figure 3–2. LIL Transfer Limits for varying ML import/export levels (ML Frequency Controller out-of-service)[13]

3.3 Further Discussion on LIL Transfer Limits

This section discusses the following additional topics with regards to LIL transfer limits:

1. Concept of "Net DC" to the Island
2. Impact of 1 or 2 SOP synchronous condensers in-service
3. Need for Avalon Generation during high Island demand

3.3.1 Net DC to the Island

3.3.1.1 During ML Export

The concept of "Net DC" to the IIS applies when the ML is exporting and can be runback to 0 MW if the LIL is lost. For example, at a 1400 MW demand level, LIL power transfer is limited to 810 MW if ML is exporting 300 MW. At the same demand level, LIL power transfer is limited to 700 MW if ML is exporting 158 MW and to 540 MW is ML is operating at 0 MW. In all of these cases, subtracting ML export from the LIL transfer limit results in a value of around 540 MW, which could be termed the "Net DC" limit. Table 3-3 shows this example, indicating that for IIS demand around 1400 MW, the maximum "Net DC" to the IIS should be limited to 540 MW.

[13] Without the ML frequency controller in service, LIL transfers must be limited in peak load conditions as explained in Section 3.2 and listed in Table 3.2. These operating points are therefore excluded from the plot.

Table 3-3. Net DC to the Island

Demand (MW)	Generation (MW)	LIL Transfer Limit (MW)	ML Export (MW)	Maximum NET DC = LIL Limit -ML Export (MW)
1821	1285	900	300	600
1400	915	840	300	540
994	589	750	300	450
1813	1214	810	158	652
1391	889	700	158	542
980	548	620	158	462
1811	1195	650	0	650
1390	872	540	0	540
972	538	450	0	450
734	384	360	0	360

Figure 3–3 graphically depicts the maximum net DC to the Island from Table 3-3. Each line on the plot represents a different ML export level.

It is evident from Figure 3–3 that the net DC to the Island is the approximately the same regardless of ML export level, as long as the ML export is runback to 0 MW when the LIL bipole is lost.

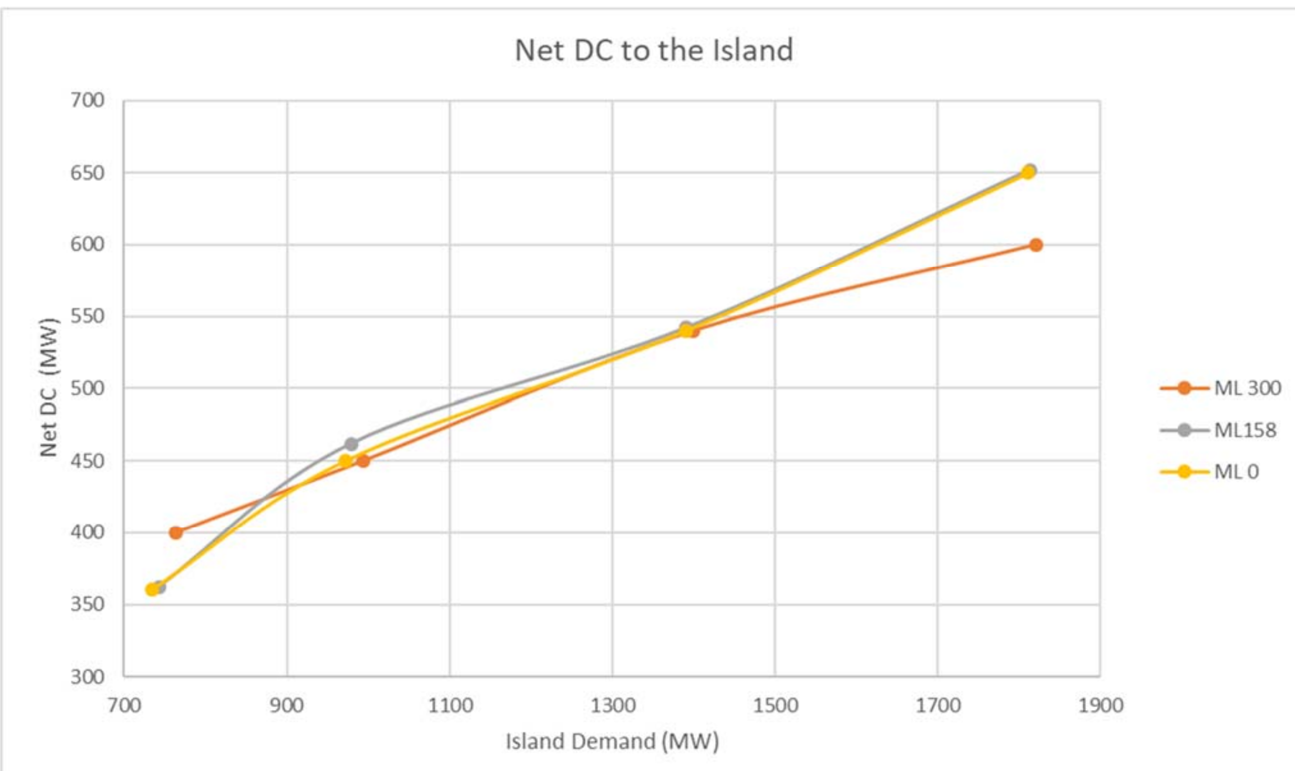

Figure 3–3. Maximum "Net DC" to the Island during ML export

3.3.1.2 During ML import

The “NET DC” concept does not apply in the same manner when the ML is importing because it cannot be runback to help the IIS frequency. However, as long import capacity is available, the ML frequency controller will provide up to 150 MW of frequency support if a LIL pole or the bipole is lost.

The LIL transfer limits in Figure 3–1 corresponding to ML at 0 MW and ML importing 150 MW are nearly identical. This is because in both cases the ML provides a fast 150 MW response to loss of the LIL infeed, resulting in a similar frequency response in the IIS.

The LIL transfer limit corresponding to ML 320 MW import is approximately 150 MW lower than the ML 0 MW and ML 150 MW import cases, because in this case the ML is already operating at the import limit and does not provide any of the 150 MW support. In this case, the ML frequency controller capacity would be set to 0 MW to ensure that Maritime Area limits are not violated. Similarly, the LIL transfer limit corresponding to ML 250 MW import is approximately 80 MW lower than the ML 0 MW and ML 150 MW import cases, because there is only 70 MW of room for the frequency controller to assist. Therefore, in some sense the Net DC concept is also evident in the ML import cases, but from the perspective of support from the ML frequency controller, not from running back the ML export.

Therefore, if the ML is importing more than 170 MW (i.e. 320-170 MW=150 MW), the LIL transfer will be begin to be limited corresponding to how much room there is left for the ML frequency controller to respond, up until it reaches the maximum of 320 MW, at which point LIL transfer is most limited.

3.3.2 Impact of SOP Synchronous Condensers

The SOP synchronous condensers provide inertia to the Island, and help the system by slowing down the rate of change of frequency immediately after infeed from the LIL is lost.

Figure 3–4 shows an example of the IIS frequency response following loss of the LIL bipole, with one (blue) and two (green) synchronous condensers in-service. It is evident that the rate of change of initial frequency decline is slower with two synchronous condensers, but that the minimum frequency dip that occurs after ~3.4 seconds is very similar in both cases.[14] Therefore, this study found no significant difference in LIL power transfer limits whether there was one SOP synchronous condenser in-service or two SOP synchronous condensers in-service. This is explained by the fact that the minimum frequency of the system following the loss of supply is highly dependent on the resulting capacity deficit as opposed to generator governor action. On this basis, the loss of supply is most effectively counteracted by load shedding, runbacks, and frequency controller action. As mentioned above, the additional inertia serves to slow down the rate of frequency decay. However, the extra time for governor action is insufficient to make an appreciable difference in frequency recovery.

[14] Both cases have very similar minimum frequencies with slight differences being attributed to variations in the electromechanical oscillations that occur as the frequency approaches 58 Hz. These variations are due to the differences in inertia in the two cases.

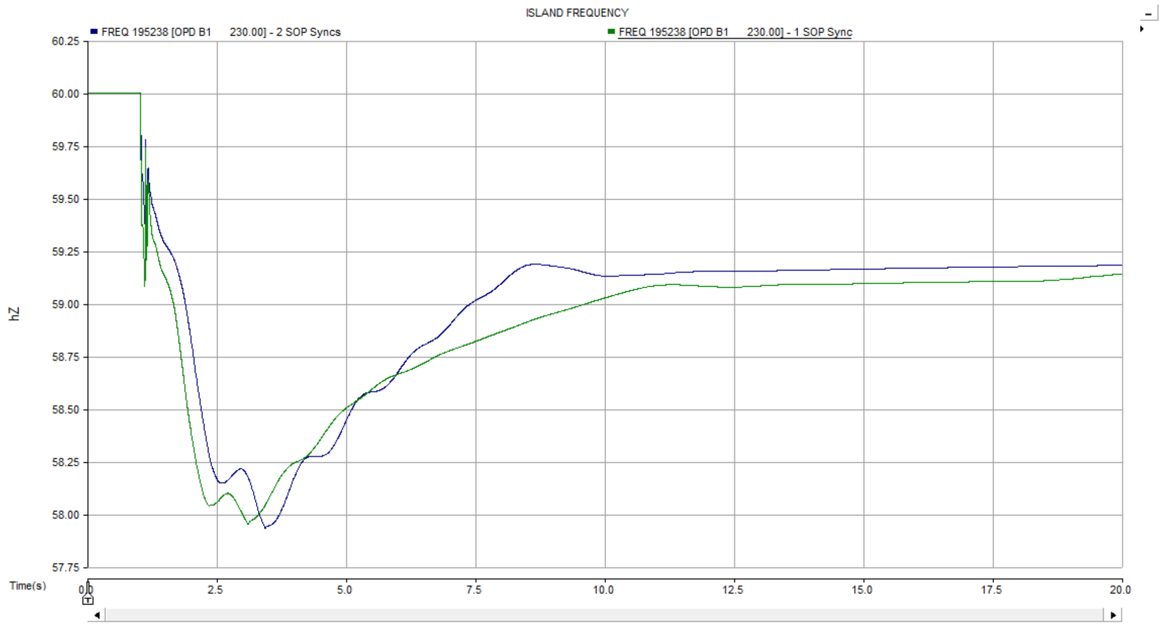

Figure 3–4. Loss of LIL bipole. Frequency response with 1 (blue) and 2 (green) SOP synchronous condensers.

3.3.3 High Island Demand – Need for Avalon Generation

High demand scenarios were seen to experience voltage collapse and system instability following loss of the LIL bipole. Previous studies[15] have identified a similar issue of voltage collapse along the Bay d'Espoir to Soldiers Pond corridor near Sunnyside. The Avalon Capacity study observed voltage collapse for three-phase faults on the 230 kV AC lines between Bay d'Espoir and Sunnyside/Western Avalon, and the Stage 4A High Power study included similar voltage collapse scenarios for 3PF on lines at BDE and following loss of the LIL bipole under peak demand. Previous studies have correlated the voltage collapse issue with high power transfer between BDE and SOP, and the need for Avalon generation to be in-service under peak Island demand.

This study found that at IIS demand levels of 1600 MW or greater, it becomes necessary to turn on Avalon generation to avoid voltage collapse in case the LIL bipole is lost. Results indicate that the voltage collapse is not a function of the pre-event LIL power flow or the 230 kV power flow to the Avalon Peninsula, but rather it is a function of the total power flow over the 230 kV corridor following the LIL trip. This is due to the lack of dynamic reactive support to withstand such significant power flows in the BDE-SOP corridor. The minimum requirement for Avalon thermal generation to offload the power flow is summarized in Table 3-4.

[15] TGS report R1529.01.02 "Solutions to Serve Island Demand during a LIL Bipole Outage", and TGS report TN1205.62.05 "Stage 4A LIL Bipole: Preliminary Assessment of High Power Operation".

Table 3-4. Minimum Avalon Thermal Generation Required to be in-service

IIS Demand (MW)	Avalon Generation (MW)
1700 - 1830	90-110
1650 - 1700	60-70
1600 - 1650	30

The following additional items are noted:

- The Come-By-Chance capacitor banks should be in-service when the power flow eastward from BDE towards SOP is high to help support the voltage if the LIL bipole is lost. Keeping the pre-contingency voltage near Sunnyside as high as possible (within criteria) improves the system response to the worst case contingencies.
- In line with previous operational studies, when power flow from BDE to SOP reaches levels around 650 MW, the IIS can also experience instability if there is a 3PF on line TL267. Therefore, power flow on this corridor should be limited to 650 MW during this transitional period from low to high power operation. The details of the operating guideline to limit power flow between BDE and SOP will be finalized during the final Stage 4 operational studies, taking into consideration all contingencies in the system including three-phase AC faults and loss of the LIL bipole.
- While it is targeted that system stability shall be maintained following the loss of the LIL bipole, this contingency is beyond the scope of Transmission Planning criteria. Results of the analysis indicate that the loss of the LIL bipole may result in transient undervoltages. Additionally, a 0.7 Hz oscillation was often observed in the voltage along the BDE to SOP corridor, as shown in Figure 3–5. This oscillation will be further assessed in the next stage of the operational studies.
- Figure 3–6 depicts the LIL transfer versus the power flowing eastward from Western Avalon (WAV) to Soldier's Pond (SOP) in order to prevent voltage collapse along the BDE-SOP corridor in case the LIL bipole trips.

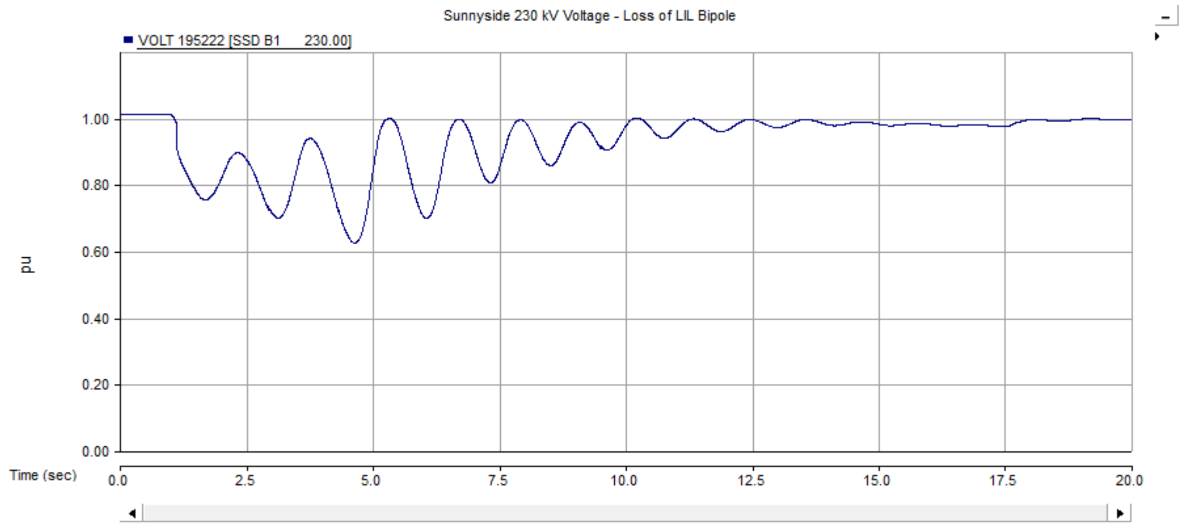

Figure 3–5. Example of SSD voltage response after loss of LIL bipole under high demand

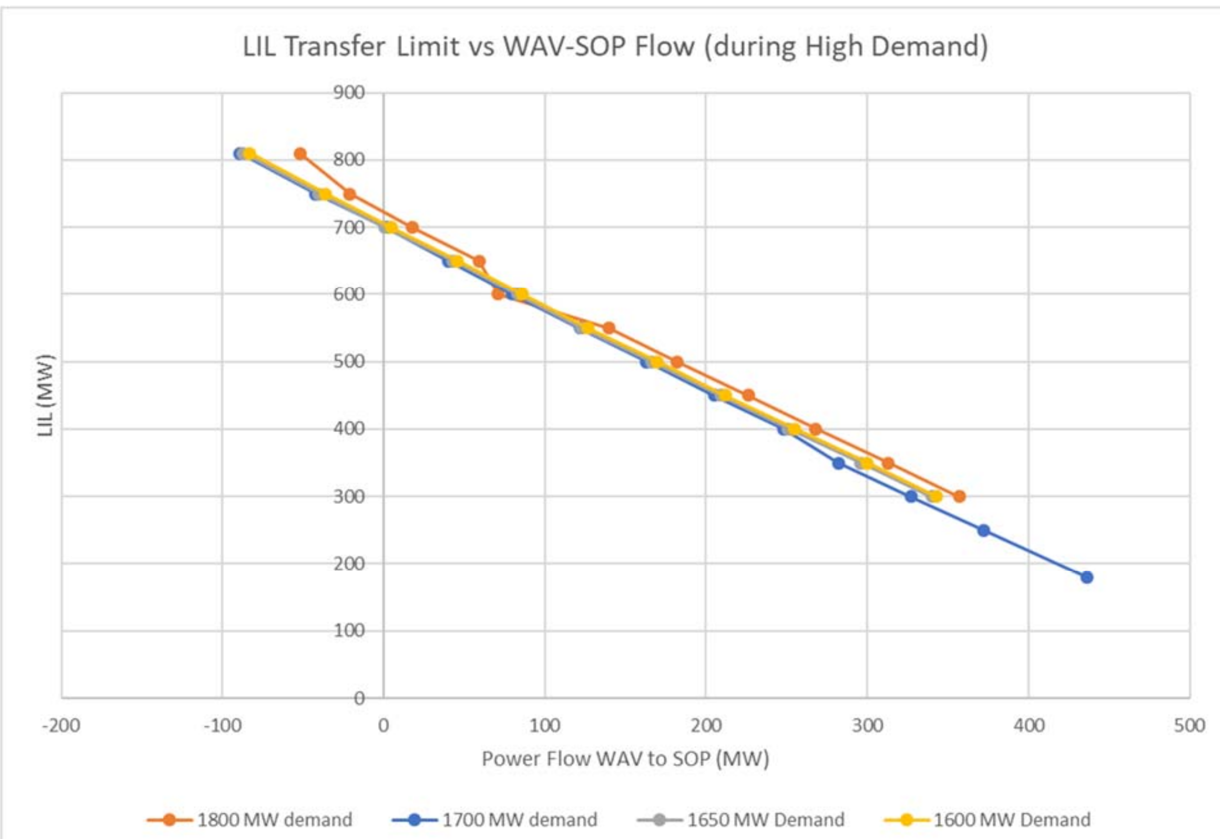

Figure 3–6. LIL Transfer vs. WAV-SOP power flow (to avoid voltage collapse if LIL bipole trips)

4. ML Transfer Limits

Loss of the ML bipole and ML pole are the contingencies that define the ML import and export limits.

If the ML bipole or pole is lost while exporting, the IIS will experience an overfrequency. Transmission Planning criteria states that this overfrequency should not go above 62 Hz.

If the ML bipole or pole is lost while importing, the IIS will experience an underfrequency. Transmission Planning criteria state that for loss of the bipole frequency should remain above 58 Hz, however controlled UFLS is permitted. For loss of a pole, the frequency should remain above 59 Hz.

Note that if an ML pole is lost, it is assumed that the healthy ML pole will pick up the transfer that was lost on the other ML pole, up to its rating of 250 MW.

Ultimately, the LIL will have a frequency controller with a small deadband that will respond to assist IIS frequency if the ML bipole or pole trips. During the transition from low to high power operation, however, the LIL frequency controller will not yet be available.

This study determined ML export and import limits for two scenarios during the transition period:

1. Without the use of LIL runbacks or runups
2. With the use of LIL runbacks and runups

4.1 Without the use of LIL Runbacks/Run-ups

ML import and export limits were first determined without the use of LIL run-ups or runbacks to establish a baseline for the ML transfer limits. These limits were determined for scenarios when there are no Holyrood (HRD) units in-service, and for scenarios where one or more HRD units are in-service. When there are no HRD units in-service, the limiting criteria for loss of ML exports is keeping the system frequency below 62 Hz. When an HRD unit is in-service, the limiting criteria for ML exports becomes ensuring that the power on the HRD units does not decrease more than 15 MW per unit as a result of the overfrequency following the loss of the ML bipole.

4.1.1 No HRD Units In-Service

These limits are listed in Table 4-1 for loss of the ML bipole and for loss of an ML pole. Red text depicts cases where loss of an ML pole is more limiting than loss of the ML bipole.

Table 4-1. ML import/export limits without LIL run-ups/runbacks – no HRD units

Import/ Export	Demand (MW)	Generation (MW)	Loss of ML Bipole		Loss of ML Pole	
			ML Transfer (MW)	Max/Min Frequency (Hz)	ML Transfer (MW)	Max/Min Frequency (Hz)
Export	1811	1213	160	62.0	160	<62.0
	1390	865	135	61.9	135	<62.0
	974	530	100	61.9	100	<62.0
	736	399	75	62.0	75	<62.0

Import/ Export	Demand (MW)	Generation (MW)	Loss of ML Bipole		Loss of ML Pole	
			ML Transfer (MW)	Max/Min Frequency (Hz)	ML Transfer (MW)	Max/Min Frequency (Hz)
	533	425	70	61.9	70	<62.0
Import	1835	1130	-320	58.1	-290	59.0
	1397	750	-240	58.1	-240	59.5
	982	537	-200	58.1	-200	59.6
	746	496	-160	58.1	-160	59.7

Since loss of an ML pole or bipole have the same 62 Hz frequency criteria, loss of an ML bipole defines the ML export limits.

The loss of supply (including the loss of a generator within the Island Interconnected System or the loss of a pole) cannot result in UFLS. The loss of an ML pole is more restrictive than the loss of the ML bipole when defining the ML import limit in the peak demand case. In all other cases, limits are defined by the loss of the bipole. This is due to the fact that the ML is equipped with pole compensation where the healthy pole will run up to a maximum of 250 MW in the event of a pole trip. In the peak load case, there is a capacity shortfall, which results in a frequency drop to 59 Hz.

Figure 4–1 graphically depicts the most limiting ML import/export limits from Table 4-1. Note the data point for the extreme light demand case during ML import from Table 4-1 is not included because it is already at minimum generation, yet loss of the ML bipole does not result in a frequency dip to the limit of 58 Hz is the ML bipole is lost. This data point would falsely skew the results.

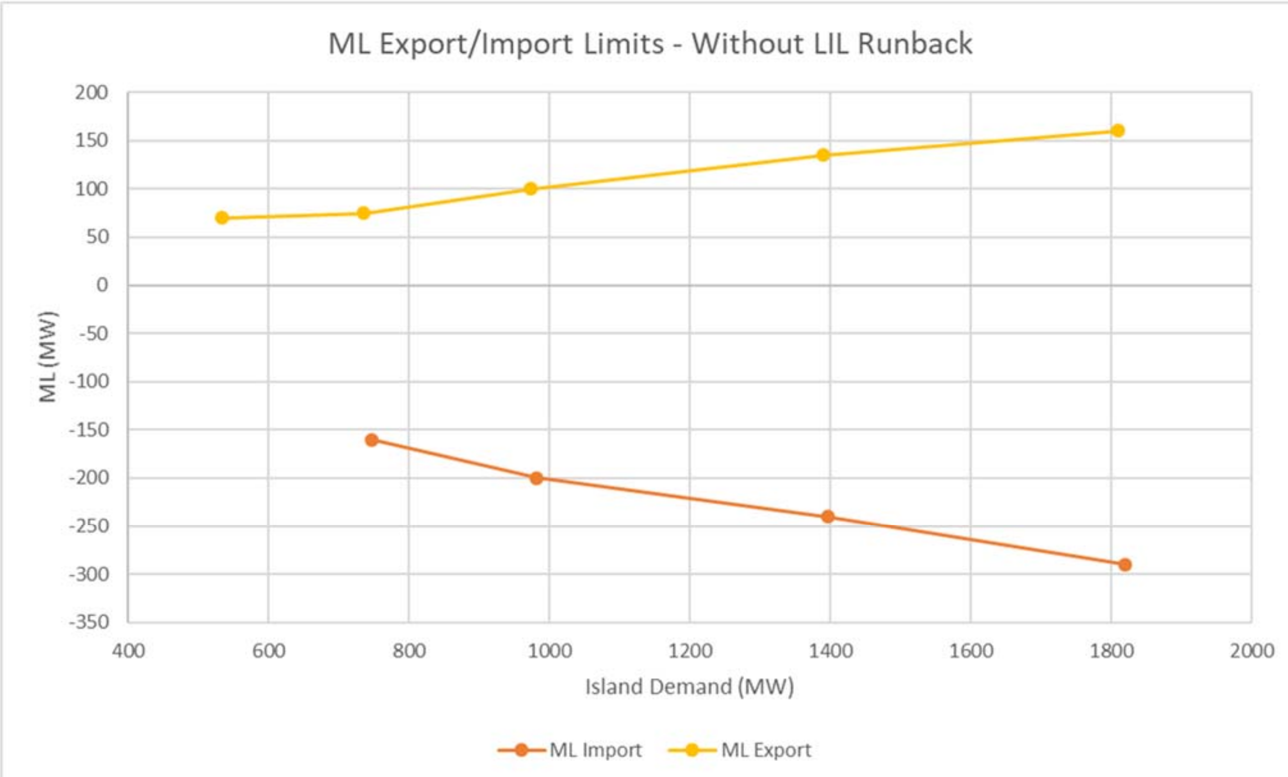

Figure 4–1. ML import/export[16] limits, without LIL run-ups/runbacks or frequency control

4.1.2 HRD Units In-Service

As mentioned earlier, with HRD units in-service, ML exports must be limited such that loss of the ML bipole does not result in more than a 15 MW decrease in power output of an HRD unit in response to the system overfrequency. ML import levels shown in Figure 4–1 are not affected when HRD units are in-service.

Figure 4–2 depicts the ML export limits with 1, 2 and 3 HRD units in-service.

[16] ML export limits in Figure 4-1 assume that no HRD units are in-service. Please see Figure 4-2 for ML export limits with HRD units in-service.

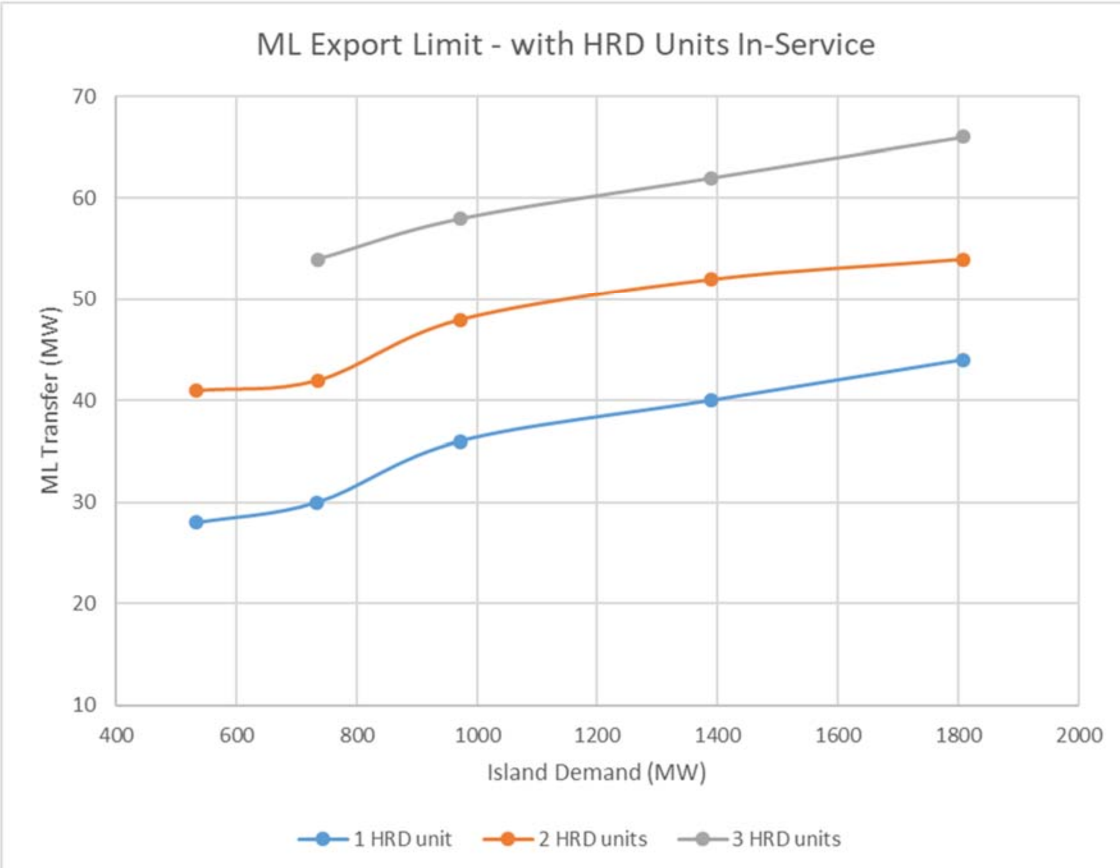

Figure 4–2. ML Export Limits with HRD units in-service

4.2 With LIL runbacks/run-ups

If LIL run-ups are used when there is loss of ML import, and LIL runbacks are used when there is loss of ML export, then the ML power transfer is not limited, and it can operate over its full range from 320 MW import to 500 MW export. This assumes that there is sufficient room available on the LIL (up or down) to cover for the loss of the ML bipole with the runbacks presented in this report.

4.2.1 ML Export Limits

Table 4-2 summarizes the minimum LIL runbacks needed to keep IIS frequency above 62 Hz following the loss of an ML pole or bipole at ML export at levels of 500 MW and 300 MW.

Table 4-2. Minimum LIL runbacks needed for loss of ML Export

Demand (MW)	Generation (MW)	ML Export (MW)	At MFA LIL Transfer (MW)	At MFA Total Runback (MW)	At SOP LIL Transfer (MW)	At SOP Total Runback (MW)	Maximum net loss of export on the IIS to meet 62 Hz (MW)
Loss of ML Bipole							
1428	1094	500	900 -> 500	400	832 -> 480	352	148
1038	703		900 -> 446	454	832 -> 432	400	100
812	476		900 -> 392	508	832 -> 380	452	48
606	402		750 -> 226	524	702 -> 222	480	20
1821	1285	300	900 ->744	156	832 -> 700	132	168
1400	915		840 -> 654	186	780 -> 618	162	138
994	589		710 -> 480	230	668 -> 464	204	96
764	404		640 -> 394	246	606 -> 380	226	74
553	400		470 -> 216	254	452 -> 212	240	60
Loss of ML Pole							
1428	1094	500	900 -> 712	188	832 -> 672	160	90
1038	703		900 -> 659	214	832 -> 626	206	44
812	476		900 -> 618	282	832 -> 588	244	6
606	402		750 -> 470	358	702 -> 452	250	0

However, rather than running back the LIL by the minimum amount needed to keep the IIS frequency below 62 Hz for each particular operating condition, a simpler approach that could be applied to all levels of ML export over all ranges of IIS demand would be to simply runback the LIL by the amount of ML export that was lost. Note that the LIL runback should be high enough at MFA to consider LIL losses, such that the total LIL runback as measured at Soldiers Pond is equal to the amount of ML export that was lost. Table 4-3 summarizes the maximum frequencies observed in the IIS using this approach for loss of the ML bipole at the maximum ML export of 500 MW.

Table 4-3. LIL Runback @ SOP = Loss of ML Export

Demand (MW)	Generation (MW)	ML Export (MW)	At MFA LIL Transfer (MW)	At MFA Total Runback (MW)	At SOP LIL Transfer (MW)	At SOP Total Runback (MW)	Maximum frequency (Hz)
1428	1094	500	900 -> 342	558	832 -> 332	500	60.2
1038	703		900 -> 342	558	832 -> 332	500	60.3
812	476		900 -> 342	558	832 -> 332	500	60.8*
606	402		750 -> 204	546	702 -> 202	500	61.3*

*These cases show some small oscillatory behaviour that will be addressed in the next stage of the operational study.

Please note that if there are HRD units in-service, LIL runback should be high enough to ensure that the maximum difference between the LIL runback as measured at Soldiers Pond and the loss of ML export is not greater than the limits shown in Figure 4–2. This will limit the decrease in power at an HRD unit to a maximum of 15 MW per unit if the ML bipole is lost.

4.2.2 ML Import Limits

Table 4-4 summarizes the minimum LIL run-ups needed to keep the frequency above 58 Hz for loss of the ML bipole and pole during maximum import of 320 MW.

Table 4-4. Minimum LIL run-ups needed for loss of ML import

Demand (MW)	Generation (MW)	ML Import (MW)	At MFA		At SOP		Maximum net loss of import on the IIS to meet 58.1 Hz (MW)
			LIL Transfer (MW)	Total Run-up (MW)	LIL Transfer (MW)	Total Run-up (MW)	
Loss of ML Bipole							
1820	974	320	0	0	0	0	320
1401	674		420->495	75	405->475	70	250
987	421		250->380	130	245->368	123	245
818	407	260*	90->288	198	89->281	192	128
Loss of ML Pole							
1824	998	320	500 -> 519	19	480 -> 498	18	52
1402	724		390 -> 418	28	378 -> 404	26	44
987	421		250 -> 279	29	245 -> 273	28	42
750	400	260*	90 -> 90	0	89 -> 89	0	0

*maximum ML import during 750 MW demand with LIL at 90 MW (minimum IIS generation)

Note that for ML import levels of 150 MW or lower, LIL run-ups are not required.

However, rather than running up the LIL by the minimum amount needed to keep the IIS frequency from going below 58 Hz for each particular operating conditions, a simpler approach that could be applied to all levels of ML import over all ranges of IIS demand would be to simply run-up the LIL by the amount of ML import that was lost. Note that the LIL run-up should be high enough at MFA to consider LIL losses, such that the total LIL run-up as measured at Soldiers Pond is equal to the amount of ML import that was lost. Table 4-5 summarizes the minimum frequencies observed in the IIS if using this approach for loss of the ML bipole at the maximum import level of 320 MW. Please note that because the LIL rectifier hits minimum firing angle when trying to run-up the LIL, the LIL cannot quite reach the run-ups required to equate the loss of import to the run-up at Soldier's Pond, however the resulting IIS frequencies for the worst case loss of 320 MW of ML import are still significantly above the 58 Hz criteria. The values in (red) text show the maximum LIL run-ups that can be achieved, and the resulting minimum IIS frequencies.

Table 4-5. LIL Run-up @ SOP = Loss of ML Import

Demand (MW)	Generation (MW)	ML Import (MW)	At MFA		At SOP		Minimum Frequency (Hz)
			LIL Transfer (MW)	Total Run-up (MW)	LIL Transfer (MW)	Total Ru-up (MW)	
1824	998	320	500 -> 860 (836)	360 (336)	480 -> 800 (774)	320 (294)	59.2
1402	724		390 -> 742 (690)	352 (300)	378 -> 698 (644)	320 (266)	58.8
987	421		250 -> 594 (546)	344 (296)	245 -> 565 (520)	320 (275)	58.8
750	400	260*	90 -> 360 (310)	270 (220)	89 -> 349 (302)	260 (213)	58.5

*maximum ML import during 750 MW demand with LIL at 90 MW (minimum IIS generation)

5. Harmonic Analysis

Harmonic analysis was performed to determine the maximum LIL transfer limits before the IEC performance limits are exceeded, as the system transitions from low power (225 MW monopole) to high power (900 MW bipole) operation.

In this study, the harmonic currents generated by the converter as given in the GE AC Filter Performance report [1] were used.

5.1 IEC Performance Limits

The performance limits according to IEC 61000-3-6 are given in Table 5-1.

Table 5-1. IEC performance limits

Odd harmonic (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic	Dh (%)	Harmonic	Dh (%)	Harmonic	Dh (%)
5	2	3	2	2	1.4
7	2	9	1	4	0.8
11	1.5	15	0.3	6	0.4
13	1.5	21	0.2	8	0.4
17≤h≤49	1.2*17/h	21<h≤45	0.2	10≤h≤50	0.19*(10/h)+0.22
THD ≤ 3%					

5.2 Muskrat Falls

5.2.1 AC system harmonic impedance

Because this study was looking at operational limits, impedance sectors were not used to represent the ac system as was the case for the contract design. Rather, the analysis was performed using power flow cases created by Hydro, where calculated impedance points at each harmonic order were considered under various operating conditions. The power flow cases used to represent the Labrador system at peak and light load scenarios are shown in Table 5-2.

Table 5-2. Loadflows considered for MFA

Number	Load Condition	Island Demand (MW)	LIL Power Transfer (MW)	Island Generation
P90	Peak	1815	689	Maximum
P50	Light	740	196	Minimum generation

The system conditions that were considered for each power flow case were:

- 1, 2, 3 or 4 MFA units in-service
- Contingencies:
    - MFA unit
    - 315 kV transmission line between Churchill Falls (CHF) and MFA out of service
    - One 735 kV transmission line between CHF and Montagnais out of service
    - Two 735 kV transmission lines between CHF and Montagnais out of service

5.2.2 Background harmonics

The measured background harmonics at CHF were increased by a factor of two[17] and applied at the MFA converter bus. Table 5-3 shows the background harmonics included in the study. The values for harmonics not included in Table 5-3 were negligible.

Table 5-3. Background harmonics applied at MFA

Harmonic	2x measured background harmonics at CHF
2	0.24
3	0.84
4	0.12
5	0.5
6	0.08
7	0.32
8	0.04
9	0.08
10	0.06
11	0.12
12	0.04
13	0.18
14	0.04
15	0.02
16	0.02
17	0.08
18	0.04
19	0.06
20	0.02
21	0.02
22	0.04

[17] Measurements were performed before the construction of Muskrat Falls Terminal Station 2. In addition, it is expected that the ac terminal station and HVdc converters will be in service before the Muskrat Falls generators. On this basis, background harmonics were doubled to provide a conservative representation of system conditions.

Harmonic	2x measured background harmonics at CHF
23	0.04
24	0.02
25	0.04
26	0.02
27	0.02
28	0.02
29	0.02
30	0.02
31	0.02
33	0.02
34	0.02
35	0.02
37	0.02
41	0.02
49	0.02

5.2.3 Results

In order to determine whether the IEC limits were met, the harmonic performance indices were calculated for four filter configurations:

- with 2A type filters in service
- with 2A type filters and 1B type filter in service
- with 2A type filters and 2B type filters in service
- with 3A type filters and 1B type filter in service

The type A filter is a triple tuned filter, tuned to harmonics 3, 12, and 23. The type B filter is a high pass filter, tuned to the 11th harmonic. The filter component data is shown in Figure 5–1 and Table 5-4.

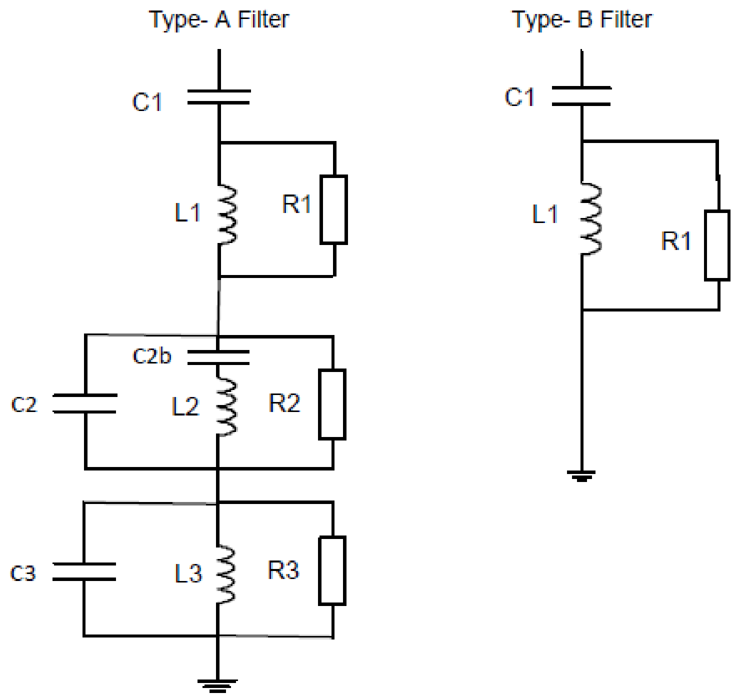

Figure 5–1. MFA filter circuit

Table 5-4. MFA filter parameters

Filter type	A	B
Nominal Mvar	72	72
system voltage (kVrms L-L)	315	315
C_1 (µF)	1.91	1.91
C_2 (µF)	13.58	-
C_3 (µF)	2.80	-
L_1 (mH)	21.03	30.5
L_2 (mH)	55.44	-
L_3 (mH)	6.98	-
R_1 (Ω)	369	388
R_2 (Ω)	443	-
R_3 (Ω)	1549	-
C_2b (µF)	126.9	-

The MFA study results are provided in Appendix 1 and 3, with values exceeding IEC limits shown in red. Note that these results are the maximum values for all cases studied, and the values for each harmonic order may not correspond to the same case.

The study results showed that the IEC limits were met in all cases for monopole operation. The LIL may therefore be operated up to 675 MW in monopole operation with:

- two A type filters in service
- two A type filters and one B type filter in service

- two A type filters and two B type filters in service
- three A type filters and one B type filter in service at Muskrat Falls

In bipole operation, the LIL may be operated up to 810 MW:

- with two A type filters in service when one or two MFA units are in service under light load conditions
- one MFA unit in service under peak load conditions

For all other cases studied, the LIL may be operated up to 900 MW in bipole operation with:

- two A type filters and one B type filter in service
- two A type and two B type filters in service
- three A type and one B type filter in service

5.3 Soldiers Pond

5.3.1 AC system harmonic impedance

Similar to Muskrat Falls, at Soldiers Pond (SOP), the study considered the calculated impedance points at each harmonic order for the power flow cases listed in Table 5-5 and for the contingencies listed below. The power flow cases represented the Island system in the year 2028 ranging from peak to extreme light load conditions.

Table 5-5. Power flows considered for SOP

Load Condition	Island Demand (MW)	ML Export (MW)	LIL Power Transfer (MW)
Peak	1815	158	689
High Intermediate-	1390	158	606
Low Intermediate	980	158	525
Light	740	158	196
Extreme Light	530	158	196

The system conditions that were considered for each power flow case included:

- 1 or 2 SOP synchronous condensers in-service
- Contingencies:
    - HRD unit
    - SOP synchronous condenser
    - 230kV transmission line between SOP and WAV out of service
    - 230kV transmission line between SOP and HRD out of service

- 230kV transmission line between SOP and HWD out of service

5.3.2 Background harmonics

For SOP, background harmonics were set in accordance with the maximum of the measured background harmonics as measured at Hardwoods Terminal Station, Western Avalon Terminal Station, and Holyrood Terminal Station.

Table 5-6 below shows the background harmonics included in the study. The values for harmonics not included in Table 5-6 were negligible.

Table 5-6. Background harmonics applied at SOP

Harmonic	Maximum measured background harmonics at HWD/WAV/HRD
2	0.02
3	1.06
4	0.08
5	1.42
6	0.03
7	0.52
8	0.01
9	0.20
11	0.10
13	0.36
14	0.01
15	0.01
16	0.01
17	0.05
18	0.01
19	0.03
20	0.01
21	0.01
23	0.05
24	0.01
25	0.07
27	0.01
29	0.02
31	0.01
35	0.01
37	0.01
41	0.01

5.3.3 Results

In order to determine whether the IEC limits were met, the harmonic performance indices were calculated for five filter configurations:

- with 1A type and 1B type filter in service
- with 1A type and 2B type filters in service
- with 2A type and 2B type filters in service
- with 2A type and 3B type filters in service
- with 3A type and 2B type filters in service

The Type A filter is a triple tuned filter, tuned to harmonics 3, 12, and 23. The Type B filter is a triple tuned filter, tuned to harmonics 11, 24, and 36. The filter component data is shown in Figure 5–2 and Table 5-7.

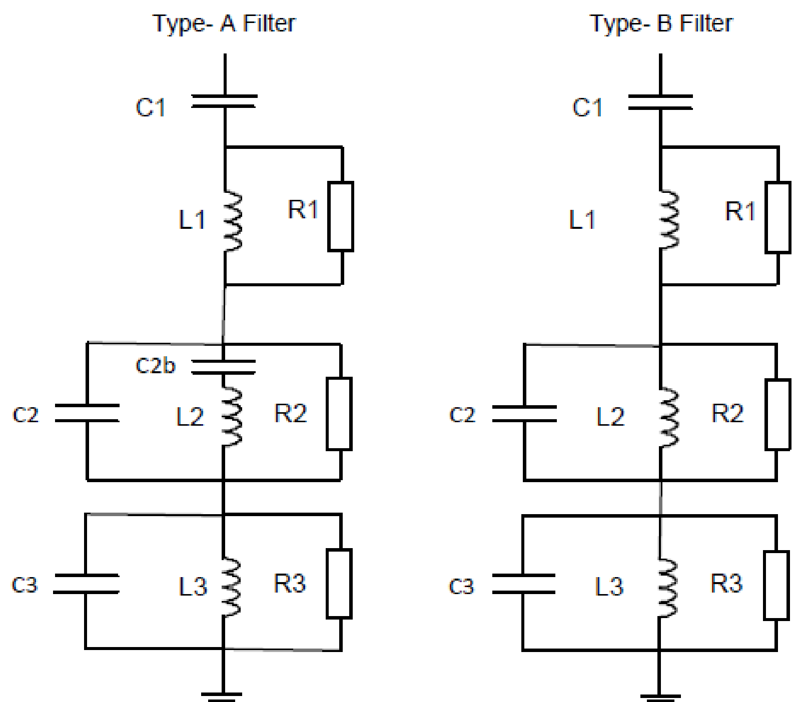

Figure 5–2. SOP filter circuits

Table 5-7. SOP filter parameters

Filter type	A	B
Nominal MVAr	75	75
system voltage (kVrms L-L)	230	230
C_1 (μF)	3.73	3.74
C_2 (μF)	17.34	4.50
C_3 (μF)	6.99	7.25
L_1 (mH)	10.72	5.15
L_2 (mH)	40.21	5.35
L_3 (mH)	2.88	1.12
R_1 (Ω)	141	170
R_2 (Ω)	514	175
R_3 (Ω)	2028	1491
C_2b (μF)	175	-

When the measured background harmonics are applied at Soldiers Pond, the IEC limits were met up to 675 MW in monopole operation and 900 MW in bipole operation.

The study results are provided in Appendix 2 and 4, with values exceeding IEC limits shown in red. Note that these results are the maximum values for all cases studied, and the values for each harmonic order may not correspond to the same case.

On the basis of the above, the LIL may be operated up to 675 MW in monopole operation or up to 900 MW in bipole operation with any of the following combinations of filters in-service:

- one A type filter and one B type filter in service
- one A type filter and two B type filters in service
- two A type filters and two B type filters in service
- two A type filters and three B type filters in service
- three A type filters and two B type filters in service

6. Conclusions

6.1 LIL Transfer Limits

LIL transfer limits are determined by loss of the LIL bipole and loss of a LIL pole. LIL transfer limits for the transitional period are shown in Figure 6–1 (ML frequency controller in-service) and Figure 6–2 (ML frequency controller out-of-service).

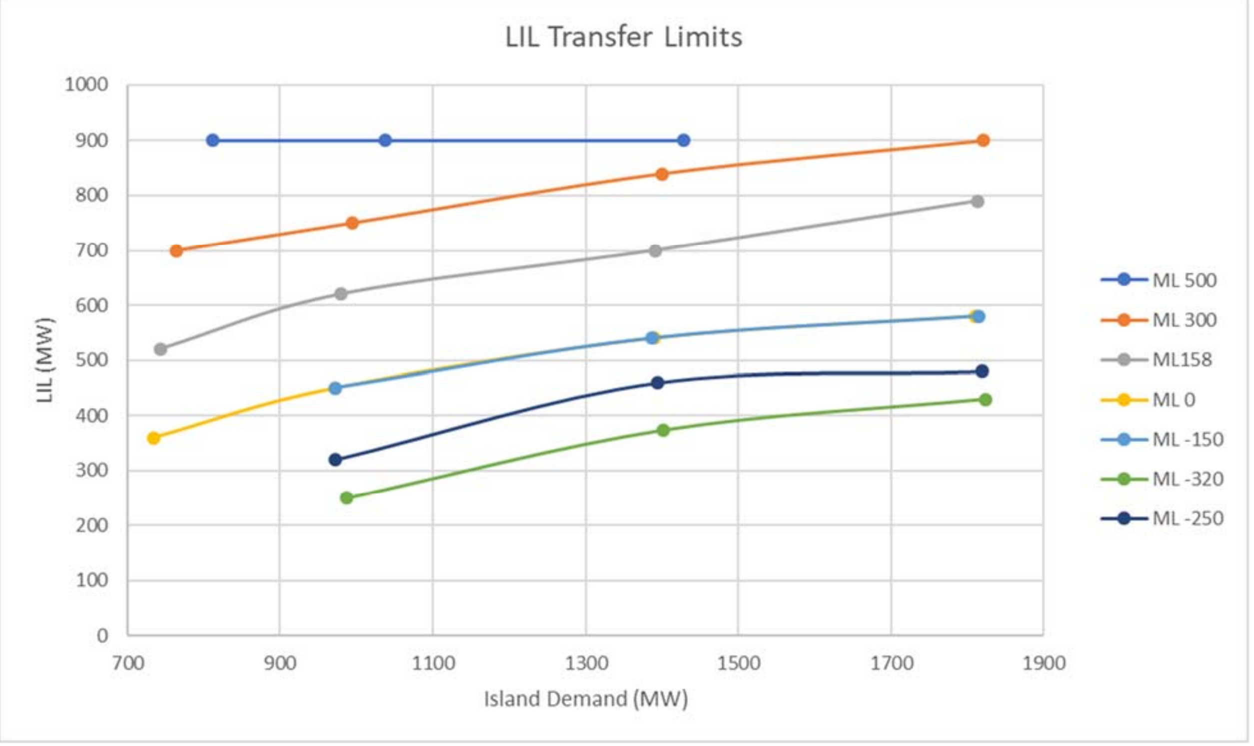

Figure 6–1. LIL Transfer Limits (ML Frequency Controller in-service)

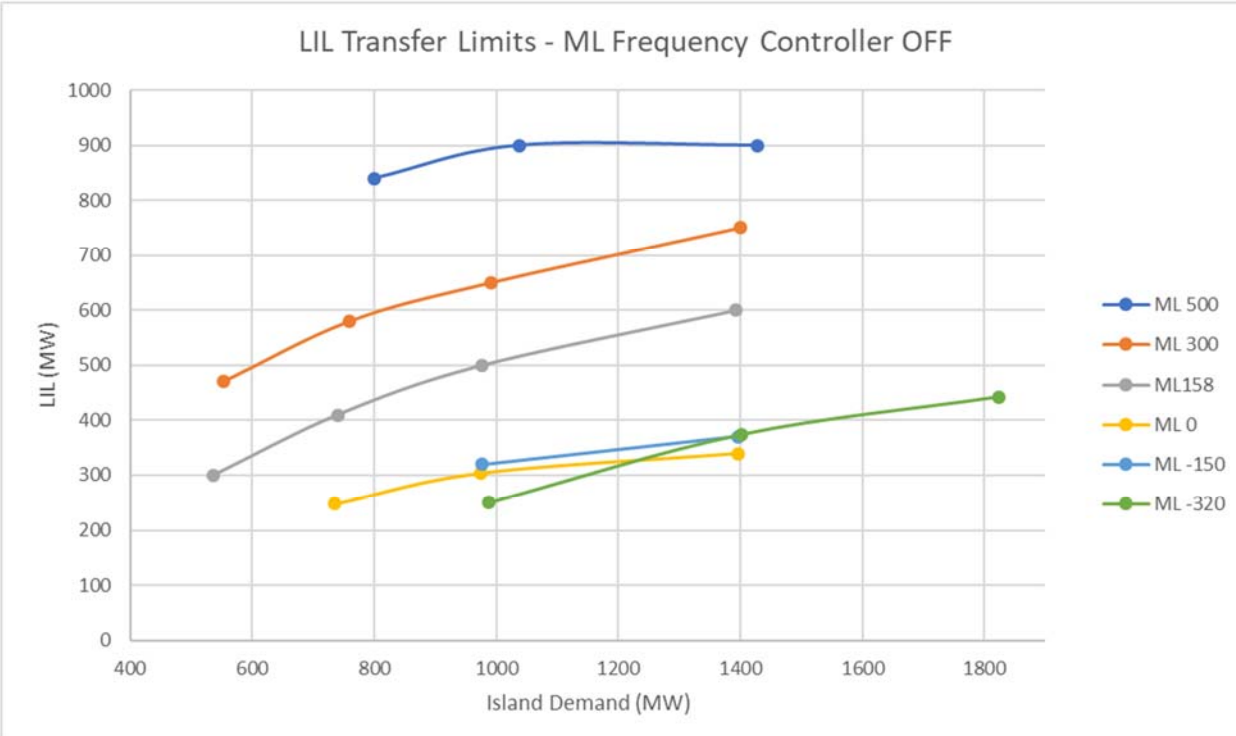

Figure 6–2. LIL Transfer Limits (ML Frequency Controller out-of-service)[18]

6.2 ML Transfer Limits

6.2.1 Without use of LIL Runbacks or Run-ups

ML transfer limits without the use of LIL runbacks or run-ups are show in Figure 6–3. Note that the ML export limits in this figure assume there are no HRD units in-service. Figure 6–4 depicts the ML export limits with 1, 2 and 3 HRD units in-service.

[18] Without the ML frequency controller in service, LIL transfers must be limited in peak load conditions as explained in Section 3.2 and listed in Table 3.2. These operating points are therefore excluded from the plot.

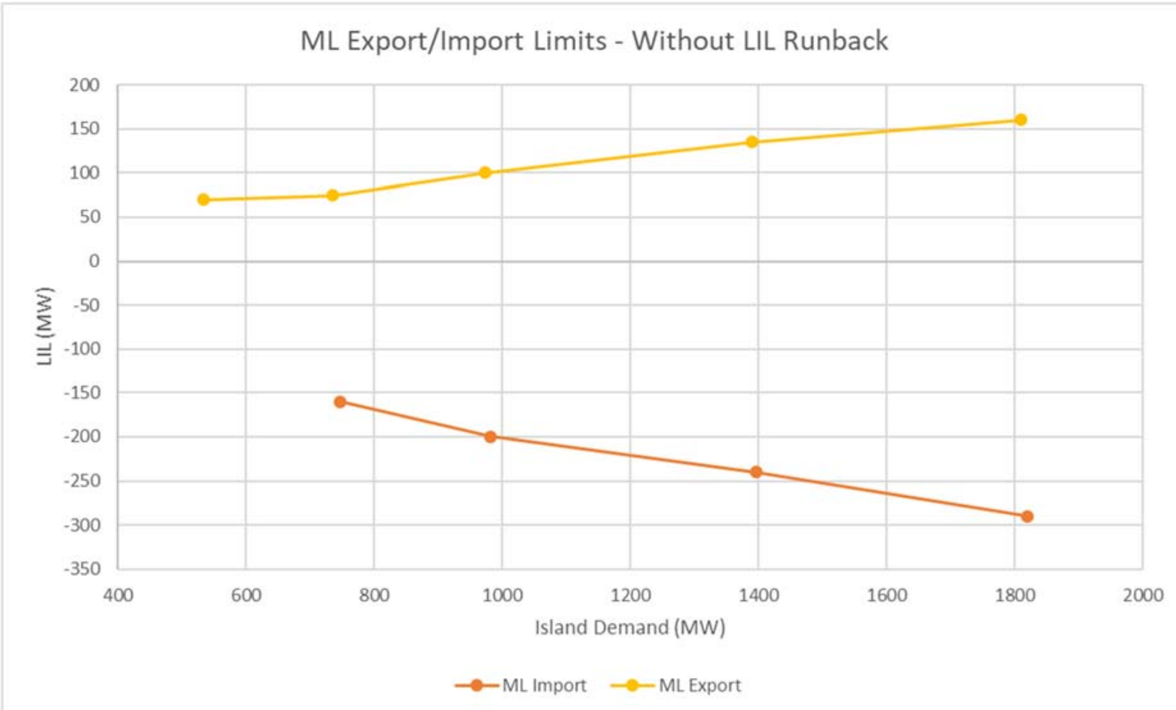

Figure 6–3. ML import/export limits, without LIL run-ups/runbacks or frequency control

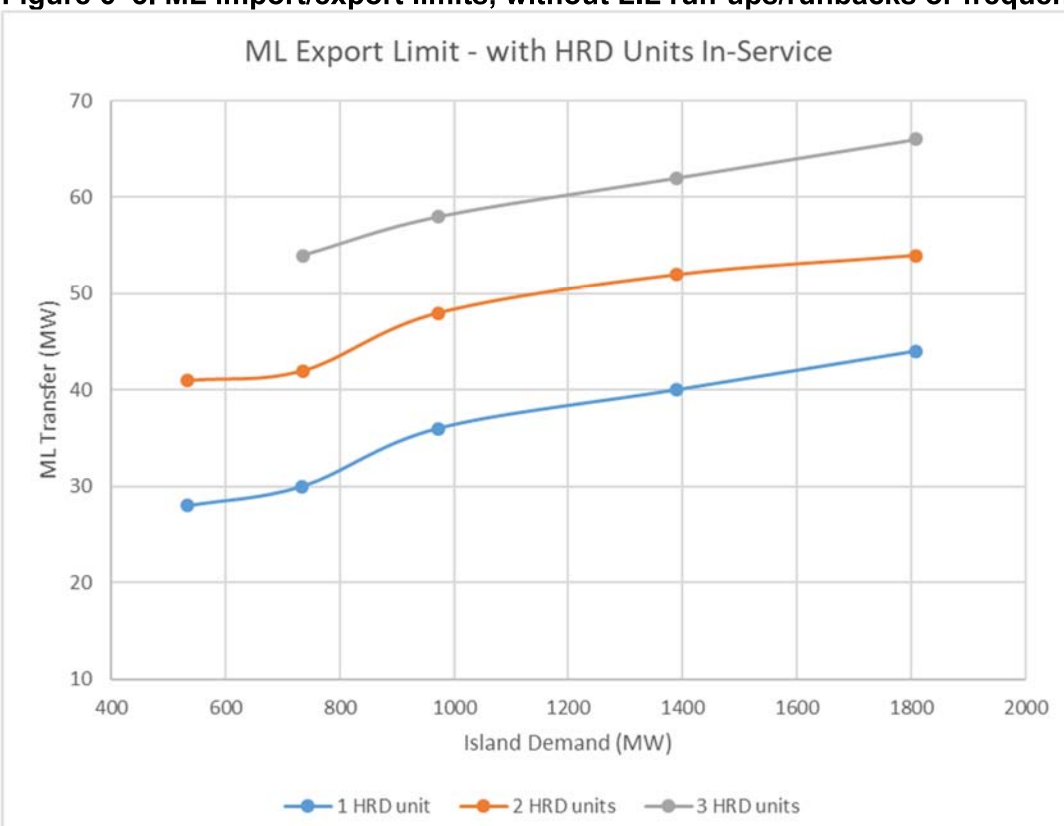

Figure 6–4. ML Export Limits with HRD Units In-service (without LIL runbacks)

6.2.2 With the use of LIL Runbacks and Run-ups

If LIL run-ups are initiated when there is loss of ML import, and LIL runbacks are initiated when there is loss of ML export, then ML power transfer is not limited, and the ML can operate over its full range from 320 MW import to 500 MW export. This assumes that there is sufficient room available on the LIL (up or down) to cover for loss of the ML bipole.

A simple approach to determine the amount of LIL runback or run-up that is required for a particular ML import or export level is to simply runback or run-up the LIL by the amount of ML export or import that was lost. Note that the LIL runback or run-up should be high enough at MFA to consider LIL losses such that the total LIL runback or run-up as measured at Soldiers Pond is equal to the amount of ML export or import that was lost. This method is applicable to all levels of ML import or export over all ranges of IIS demand.

6.3 Additional Conclusions

The following additional conclusions were made during the study.

1. **Need for Avalon Generation during High Island Demand**
   The IIS can become unstable if the LIL bipole trips during high IIS demand. The instability is due to a voltage collapse that occurs faster than the frequency decay that would trigger UFLS. It was determined that a minimum amount of Avalon thermal generation (as defined in Table 6-1) is required to be in-service when IIS demand is greater than 1600 MW to prevent system instability if the LIL bipole is lost. The Come-By-Chance capacitor banks should also be in-service (as many as steady state voltage allows) when the power flow eastward from BDE towards SOP is high to help support the voltage if the LIL bipole is lost. Note, however, that despite these mitigation measures, a 0.7 Hz oscillation in the voltage and violations of transient voltage criteria along the Bay d'Espoir to Soldiers Pond corridor were still observed in peak demand cases with high BDE to SOP power flow if the LIL bipole trips. Further investigation is required to see if the voltage response can be improved.

   Table 6-1. Minimum Avalon Generation Required to be in-service

IIS Demand (MW)	Avalon Generation (MW)
1700 - 1830	90-100
1650-1700	60-70
1600-1650	30

   Additionally, in line with previous operational studies[19], when power flow from BDE to SOP reaches levels around 650 MW, the IIS can also experience instability if there is a 3PF on line TL267. Therefore, power flow on this corridor should be limited to 650 MW during this transitional period from low to high power.

[19] TGS report R1529.01.02 "Solutions to Serve Island Demand during a LIL Bipole Outage", and TGS report TN1205.62.05 "Stage 4A LIL Bipole: Preliminary Assessment of High Power Operation".

2. **Impact of SOP Synchronous Condensers on LIL Transfer Limits**
The SOP synchronous condensers provide inertia to the Island, and they help the system by slowing down the rate of change of frequency immediately after infeed from the LIL is lost. It was found that although they slow down the initial rate of change of frequency, they do not impact the minimum frequency dip that occurs, and therefore the transfer limits defined in this study were the same whether one or two SOP synchronous condensers were in-service.

3. **Concept of "Net DC"**
The concept of "Net DC" to the IIS applies when the ML is exporting and can be runback to 0 MW if the LIL bipole is lost. Figure 6–5 shows the approximate "Net DC" limits when the ML is exporting. Note that the "Net DC" limits are very similar for various ML export levels.

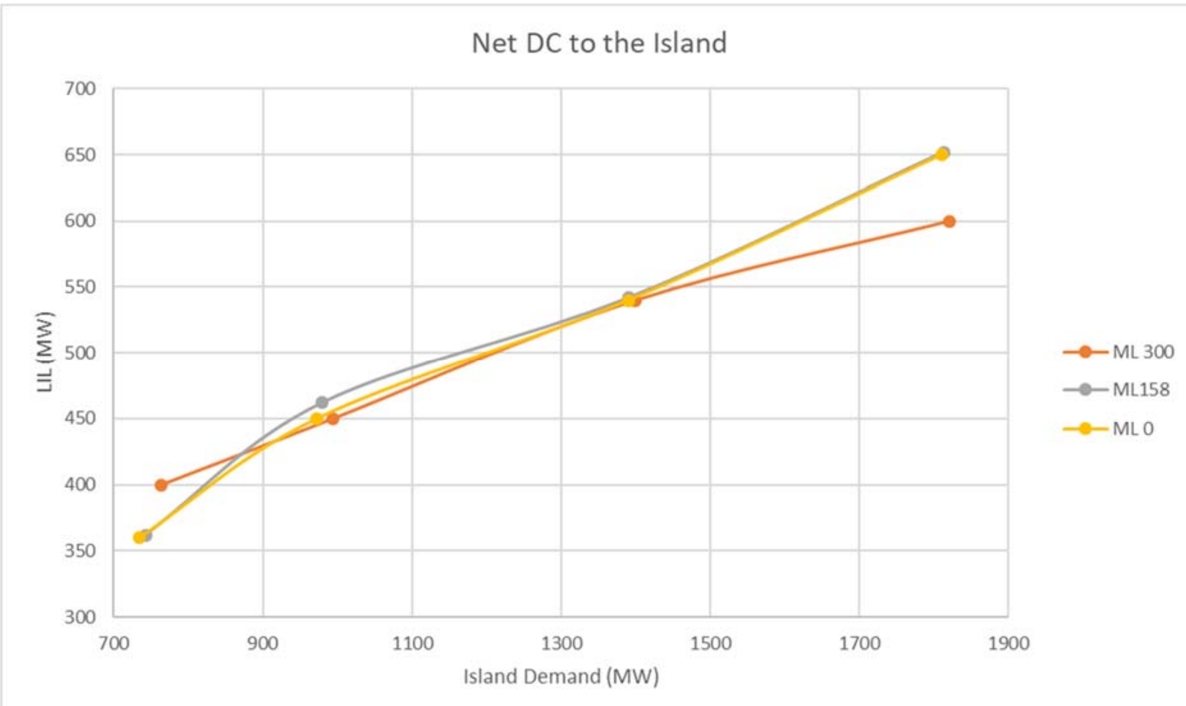

Figure 6–5. Maximum "Net DC" to the Island during ML export

6.4 Harmonic Analysis

In order to meet IEC harmonic limits, the analysis concluded that the LIL may be operated up to 675 MW in monopole operation and 900 MW in bipole operation with the filter configurations listed in Table 6-2.

Table 6-2. LIL limits and filter configurations to meet IEC harmonic limits

Monopole Operation up to 675 MW		Bipole Operation up to 900 MW	
Muskrat Falls	**Soldiers Pond**	**Muskrat Falls**	**Soldier's Pond**
two A type	one A type, one B type	two A type filters**	one A type, one B type

Monopole Operation up to 675 MW		Bipole Operation up to 900 MW	
Muskrat Falls	**Soldiers Pond**	**Muskrat Falls**	**Soldier's Pond**
two A type, one B type	one A type, two B type	two A type, one B type	one A type, two B type
two A type, two B type	two A type, two B type	two A type, two B type	two A type, two B type
three A type, one B type	two A type, three B type	three A type, one B type	two A type, three B type
	three A type, two B type		three A type, two B type

****** except when only one or two MFA units are in service under light load conditions, or when only one MFA unit is in service under peak load conditions, in which case, operation is possible only up to 810 MW with two A type filters