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

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

A. Please see the attached documents, as listed below, prepared by SNC-Lavalin as part of the Lower Churchill Project and as required by Hydro's System Planning department for the integration of the Lower Churchill Project into the Island Interconnected System.

- Reactive Power Studies (December 7, 2011) NP-NLH-108, Attachment 1
- Stability Studies (March 6, 2012) NP-NLH-108, Attachment 2
- Harmonic Impedance Studies (March 6, 2012) NP-NLH-108, Attachment 3
- Load Flow and Short Circuit Studies (April 5, 2012) NP-NLH-108, Attachment 4
- HVdc System Modes of Operation and Control Strategies Study (April 17, 2012) NP-NLH-108, Attachment 5

SNC·LAVALIN

nalcor energy

Lower Churchill Project

REACTIVE POWER STUDIES

SLI Document No.: 505573-480A-47ER-0006-01

Nalcor Reference No.: LCP-SN-CD-8000-EL-SY-0001-01-B2

Date: 07-Dec-2011

Prepared by: Umar Ahmed

Verified by: Peter Anderson

Approved by: Satish Sud

Revision					Remarks
N°	By	Verif.	Appr.	Date	
01	UA	PA	SS	07-Dec-2011	Issued for Use
00	UA	PA	SS	10-Nov-2011	Issued for Use

TABLE OF CONTENTS

Page No.

List of Figures

List of Tables

1 INTRODUCTION

This Report presents the results of the reactive power studies carried out to examine the steady-state reactive power capabilities of the ac systems at the converter ac buses with the HVdc interconnections between Muskrat Falls and Soldiers Pond (Labrador Island Link(LIL)) and between Bottom Brook and the Nova Scotia power system (Maritime Link(ML)). The present Basis of Design considers, for the LIL, a dc voltage level of ±350 kV and a nominal bipole rating of 900 MW and, for the ML, a dc voltage level of ±200 kV and a nominal bipole rating of 500 MW. This is interpreted to mean that these rated power levels and rated voltages apply at the rectifier ends (Muskrat Falls and Bottom Brook).

The LIL will be essentially uni-directional from Labrador to Newfoundland, although there will be nothing in the design of the link to prevent operation in the reverse direction. The ML is required to have a 500 MW continuous capability in bipolar mode in both directions.

Starting from the base case scenarios provided by Nalcor, the present studies are designed to determine the maximum and minimum levels of reactive power that can be provided/absorbed by the ac systems in both normal and single contingency outage conditions. These limits will be used by the converter manufacturer in the design of both the converters themselves and the associated harmonic filter banks, if these are required.

2 STUDY BASIS

Nalcor provided nineteen base case scenarios for examination. These scenarios are presented in Table 2-1.

Load flow studies were carried out for each scenario, considering normal system conditions (all equipment in service) and outage conditions. In addition to pole outages on the two dc links, the automatic sequential contingency feature of PSS®E was used to examine all single contingency outages on the ac systems.

In these studies, the converter station was represented by a fixed MW load, equal to the dc power level (positive for a rectifier, negative for an inverter) and an infinitely variable reactive power source using a static var compensator or generator with zero MW output connected to the system ac bus of the converter station. The target voltage at the system ac bus of the converter station was set at the upper and lower limits, defined by the system planning and operating criteria and the output of the reactive power source was recorded. This was carried out for each converter station for normal and all single contingency outages on the ac system. For cases where voltage violations occurred on system buses close to the converter station, the target voltage was adjusted slightly to bring these neighbouring buses within the voltage criteria. This process was repeated over the feasible operating range of the converters to produce reactive capability curves for each converter station. The MW levels on the LIL and ML were adjusted within feasible limits for each scenario, based on the system load level and generation available on the Island. Because the rated power level on the LIL represents more than 50% of the winter peak load on the Island, it was not possible to vary the converter power levels over the full range (rated power to zero power) in all cases without exceeding the capabilities of the Island generation. The power range for the LIL was extended as far as possible by reducing the export over the ML, thus allowing a reduction in the power imported over the LIL. These power levels do not necessarily represent desirable or realistic operating conditions.

The base case load flows for each scenario are presented in Appendix A.

To support the dc infeed, NLH will operate a number of thermal generating units as synchronous condensers. Of relevance to these studies are the Holyrood units 1-3, out of which unit 2 (194.4 MVA) and unit 3 (177.2 MVA) will be operated as synchronous condensers, with unit 1 (194.4 MVA) assumed out of service for maintenance. Two gas turbines at Hardwoods will also be in place by 2017 each with a rating of 63.5 MVA and both of these units will normally be operated as synchronous condensers. There is a similar unit at Stephenville but this was considered to be out of service.

The generators at Muskrat Falls (4x206 MW) were represented by units with a rated power factor of 0.9.

Table 2-1: Base Case Scenarios

No.	NLH System Load	NS Export Bottom Brook	Island Import Muskrat Falls/Soldiers Pond	Island Generation	Comments
BC-1	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 3-units @ Muskrat Falls
BC-2	Peak-2017(1552MW)	239MW	900/814MW	Maximum	Winter Peak 3-units @ Muskrat Falls
BC-3	Peak-2017(1552MW)	158MW	798/730MW	Maximum	Winter Peak
BC-4	Peak-2041(1900MW)	0MW	900/814MW	Maximum	Winter Peak
BC-5	Intermediate-2017(1100MW)	158MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-6	Intermediate-2017(1100MW)	158MW	276/268	Maximum	Spring/Fall day
BC-7	Intermediate-2017 (1100MW)	500MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-8	Light (700MW)	158MW	420/400MW	Minimum	Summer day
BC-9	Light (700MW)	158MW	81/80MW	Economic Dispatch	Summer day
BC-10	Light (700MW)	500MW	900/814MW	Economic Dispatch	Summer day
BC-11	Extreme Light (420MW)	0MW	81/80MW	Economic Dispatch	Summer night
BC-12	Extreme Light (420MW)	320MW	81/80MW	Economic Dispatch	Summer night
BC-13	Extreme Light (420MW)	320MW	457/435MW	Minimum	Summer night
BC-14	Peak-2017 (1552MW)	-260MW	286/260MW-Monopole	Maximum	Winter Peak
BC-15	Intermediate-2017(1100MW)	158MW	378/333MW-Monopole	Economic Dispatch	Spring/Fall day
BC-16	Light (700MW)	500MW	638/518MW-Monopole	Minimum	Summer day
BC-17	Extreme Light (420MW)	0MW	215/200MW-Monopole	Minimum	Summer night
BC-18	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls
BC-19	Intermediate-2017(1100MW)	500MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls

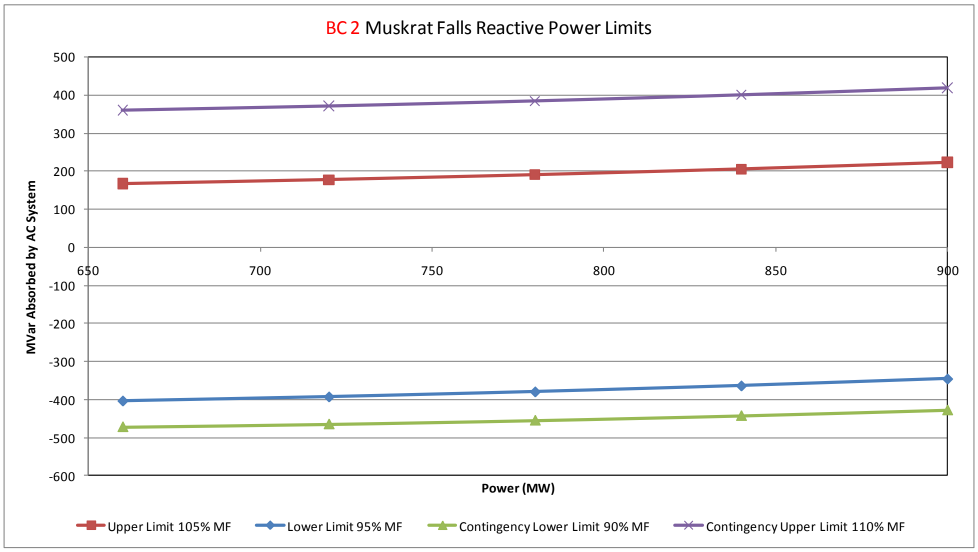
3 RESULTS OF THE STUDIES

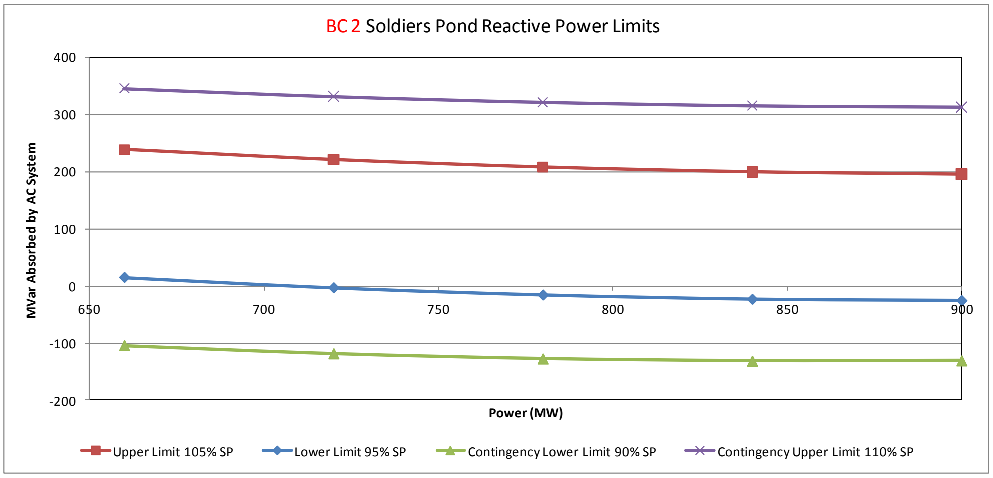
The base case and contingency load flow results for each scenario were examined. The following figures present the reactive limits for a number of representative cases.

- Figure 3-1: BC-2, Winter Peak/LIL 900 MW/ML 239 MW
- Figure 3-2: BC-7, Intermediate/LIL 900 MW/ML 500 MW
- Figure 3-3: BC-13, Extreme Light/LIL 435 MW/ML 320 MW

The plots show the reactive power that can be absorbed by the ac system at different levels of dc power at the converter bus. Thus, positive values represent reactive power absorption by the ac system and negative values represent reactive power supplied by the ac system.

Figure 3-1: BC-2, Winter Peak/LIL 900 MW/ML 239 MW





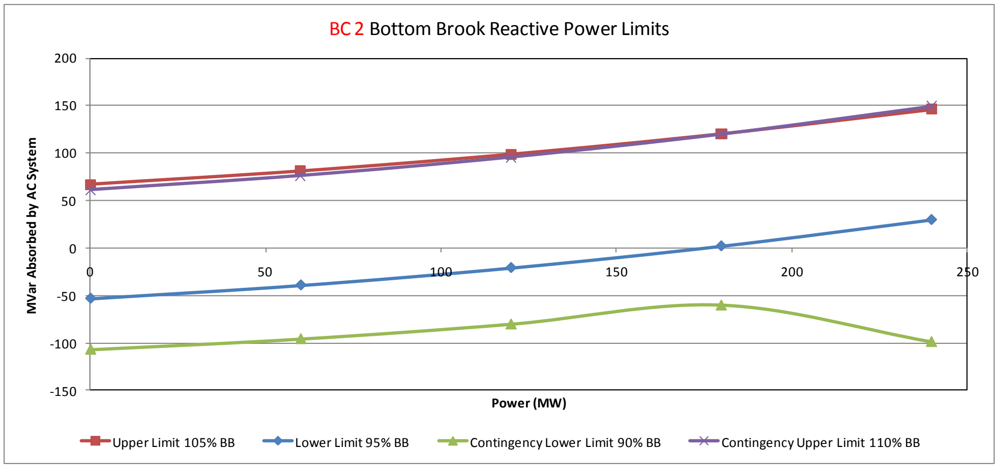
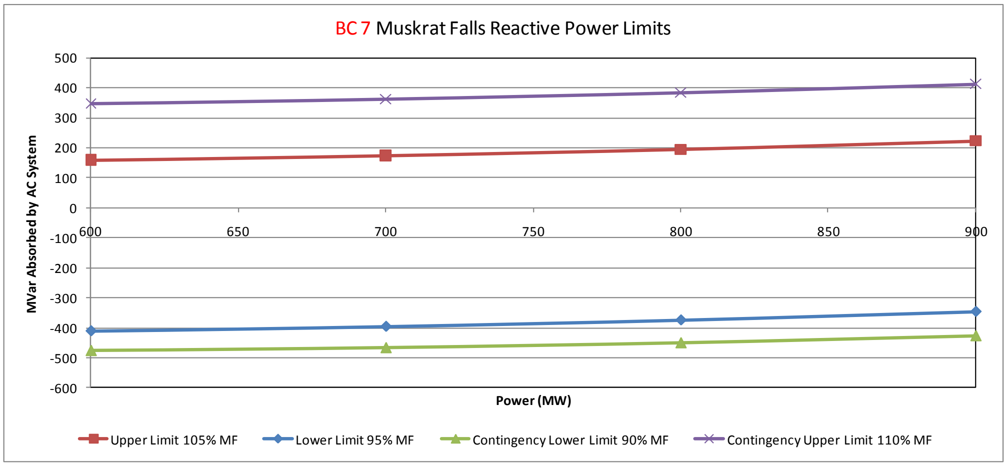
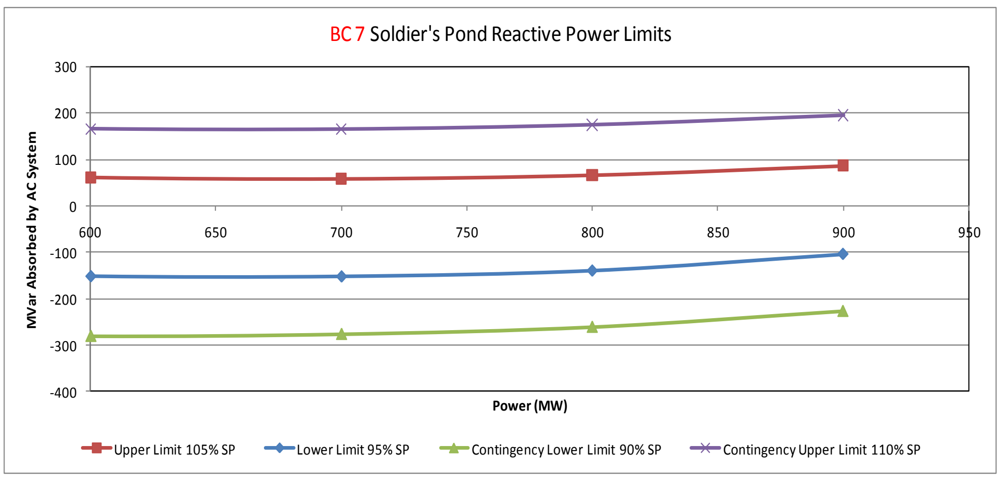


Figure 3-2: BC-7, Intermediate/LIL 900 MW/ML 500 MW





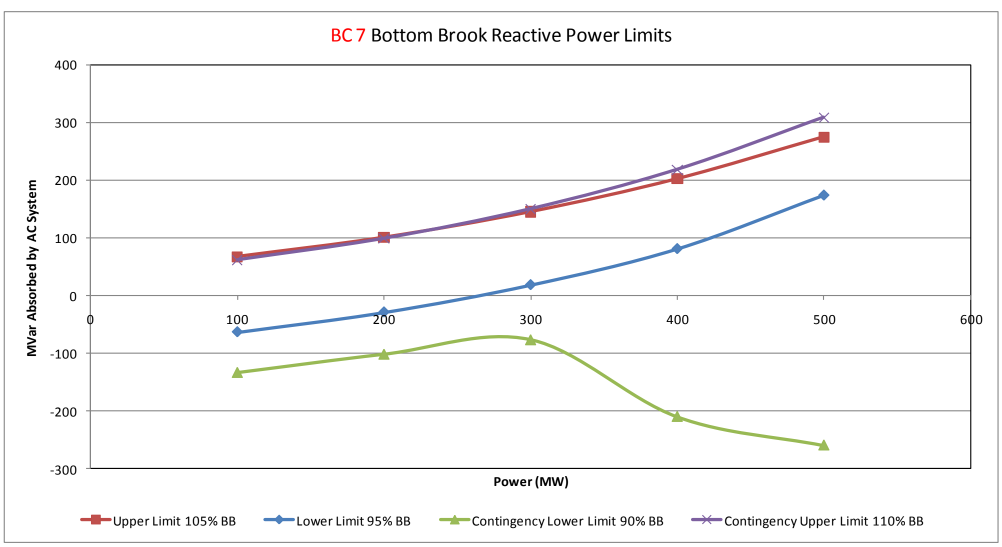
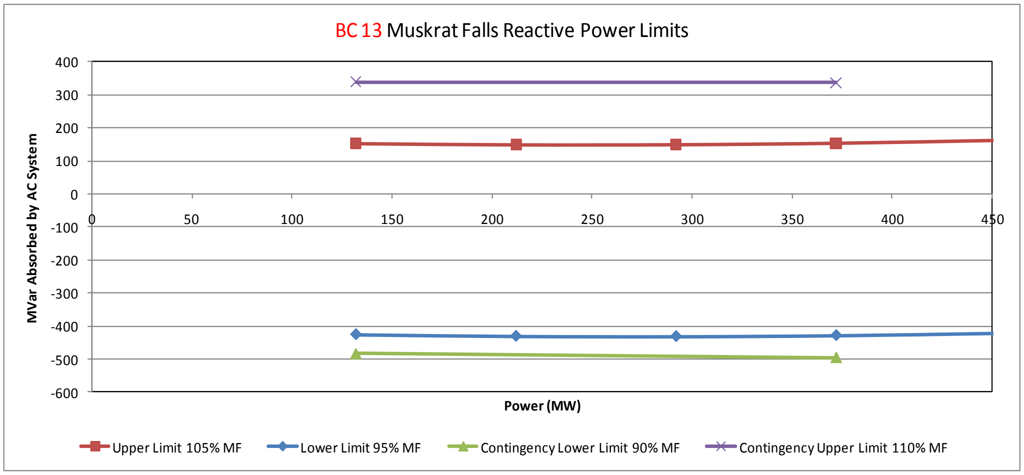
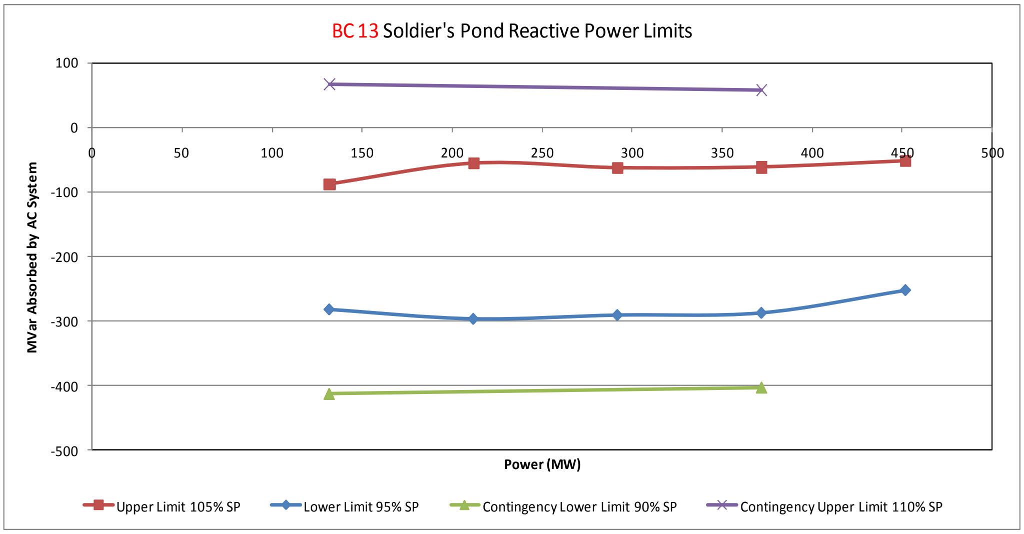
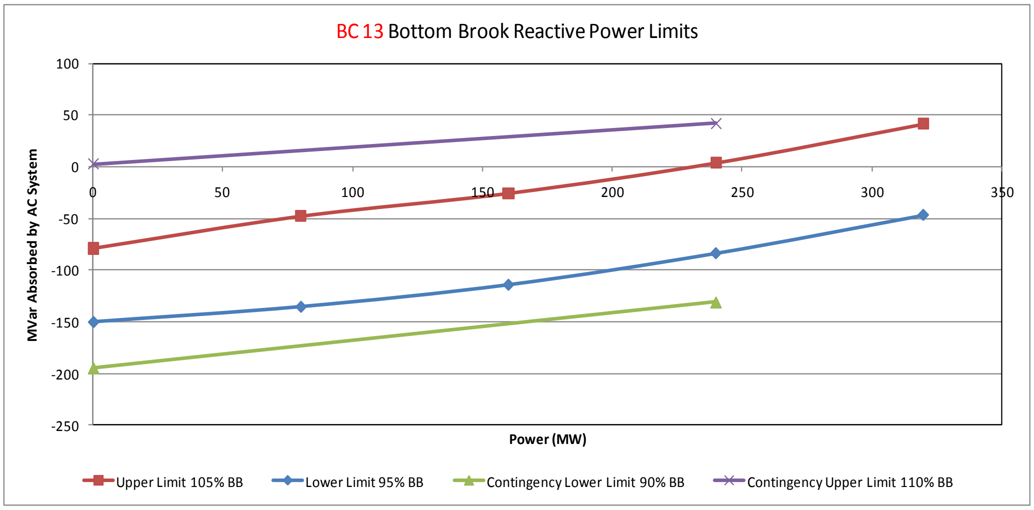


Figure 3-3: BC-13, Extreme Light/LIL 435 MW/ML 320 MW







These figures demonstrate that the minimum levels of reactive power capability occurred under base case conditions with the lower margin on acceptable voltages (±5%). The reactive power capability of the ac system was equal to or greater under contingency conditions with the higher voltage margin (±10%). Therefore, all subsequent results are shown for base case conditions only.

For the Bottom Brook converter under Scenarios BC-2 and BC-7, it may be noticed that the reactive power being absorbed by the reactive source at the converter bus under contingency conditions changes its direction above a certain dc power level. This reversal of the direction of change in reactive power is an indicator of voltage instability at that bus. This suggests that some form of dynamic reactive control, such as a static var compensator or the use of VSC technology in the converter, may be required at Bottom Brook.

3.1 Island Link-Muskrat Falls Converter Station

For normal system conditions, with all equipment in service, the voltage limits were taken as ±5% of nominal voltage. The dc power level was varied between 900 MW and zero. This variation in power level was achieved by considering a number of the base case load flows from peak load down to minimum load as the starting points. The resulting reactive power limits are shown in Figure 3-4.

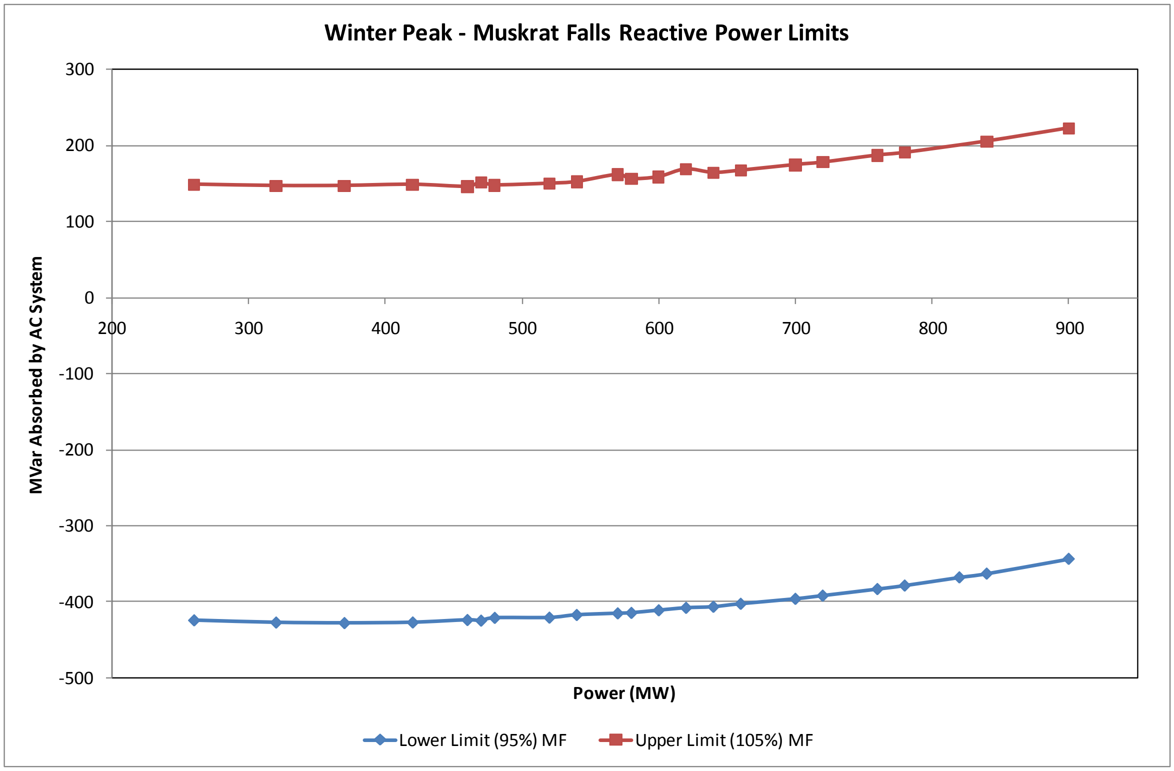
It can be seen that the margin between the upper and lower reactive limits is fairly constant over the whole range of dc power for each season. The following approximate average margins were observed between the upper and lower reactive limits:

Table 3-1: Muskrat Falls Reactive Power Margins

Season/ Load Level	Margin (upper-lower)-MVAr
Winter/Peak	575
Spring-Fall/Intermediate	570
Summer Day/Light	695
Summer Night/Extreme Light	580

There is little variation in the absolute values of reactive power or the margin over the different seasons except for the summer day light load condition where a larger margin is observed. As shown in Figure 3-5, the variation between seasons is relatively small over the entire dc power range. Thus it would be feasible to consider a single set of upper and lower limits that would apply over the whole year and at any load level. The minimum margin of 570 MVAr from above represents 63% of the rated converter power of 900 MW.

Figure 3-4: Muskrat Falls Reactive Power Limits



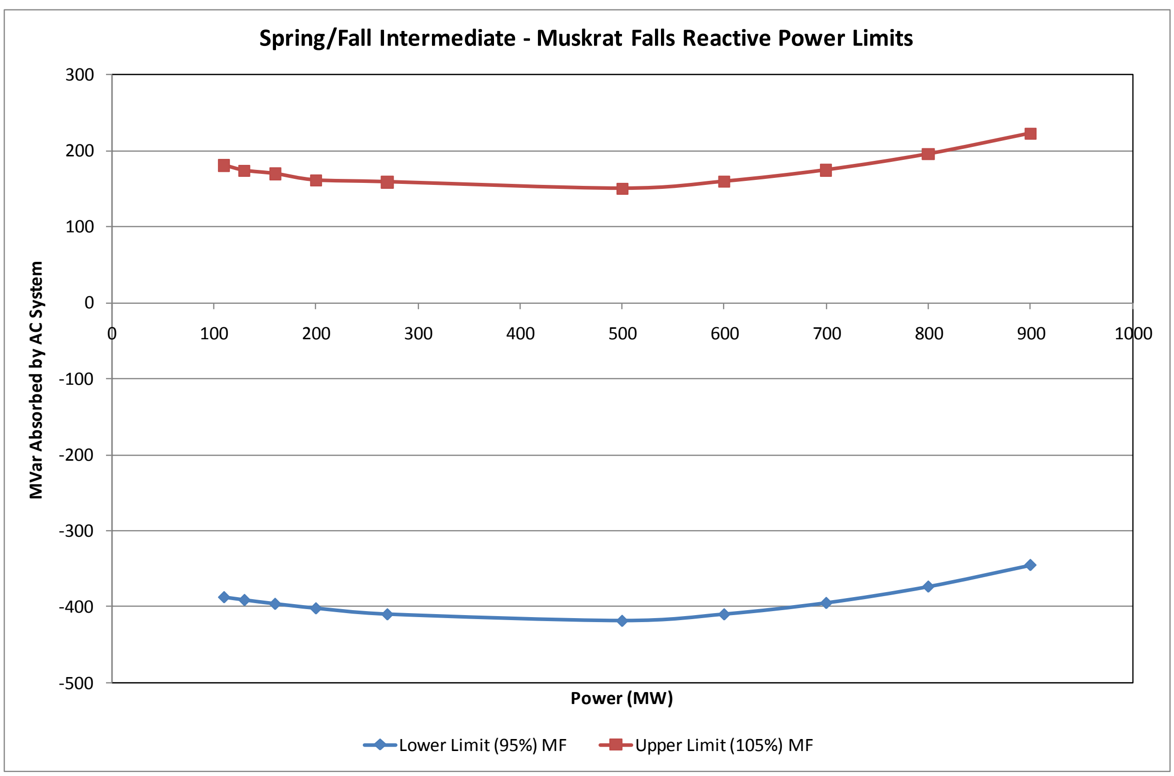
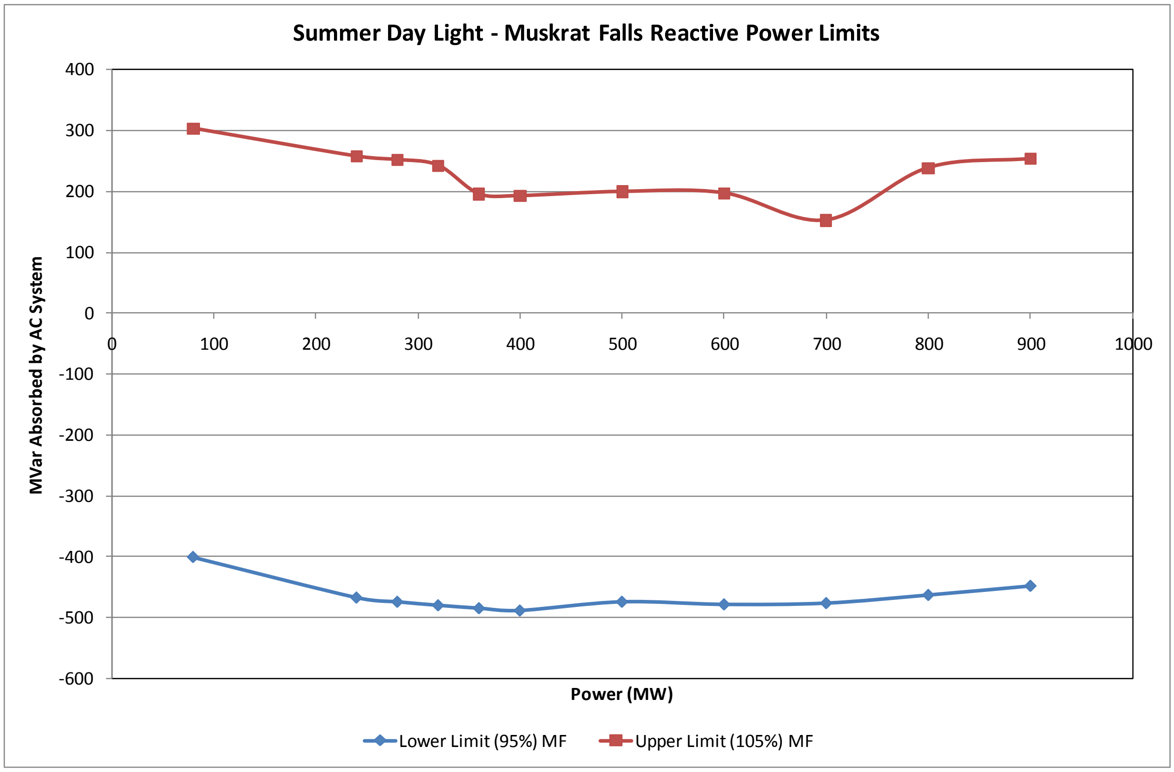


Figure 3-4: Muskrat Falls Reactive Power Limits



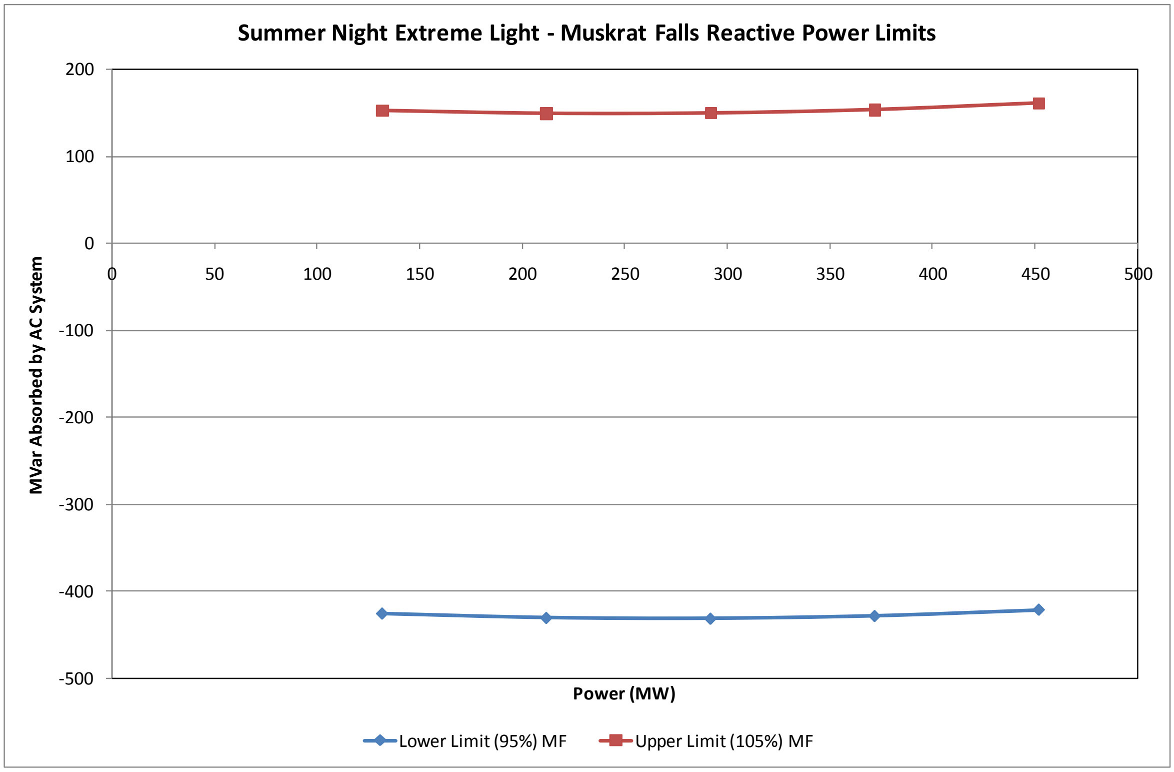
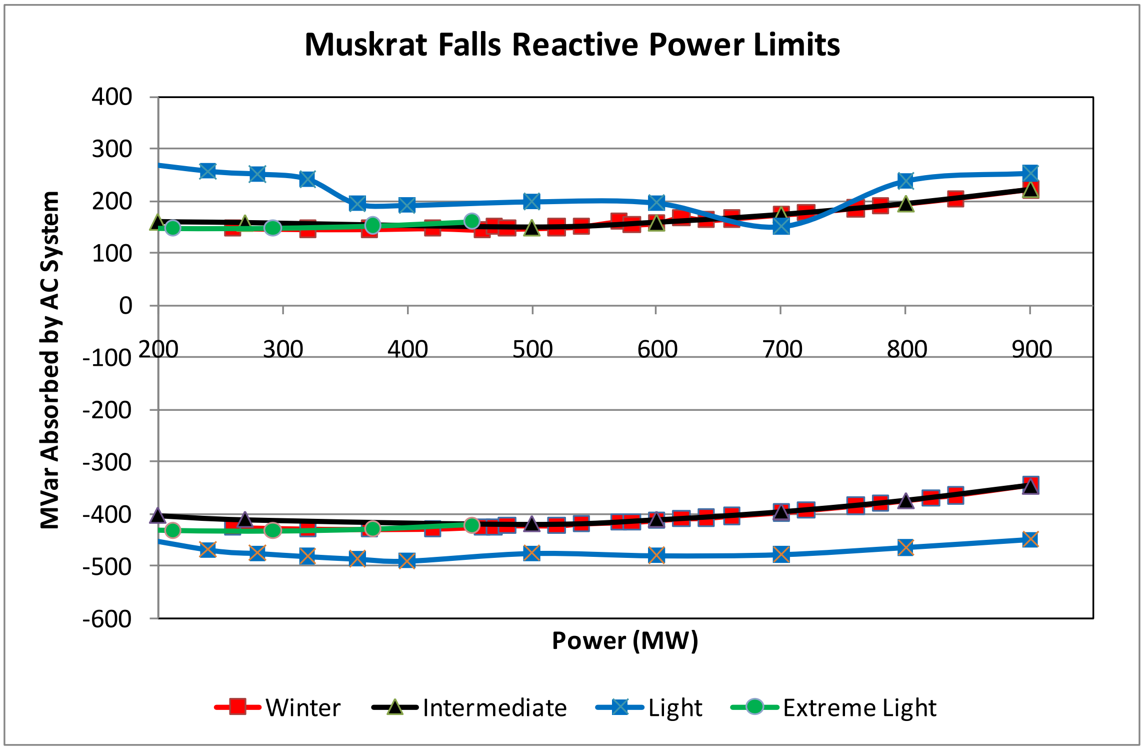


Figure 3-5: Muskrat Falls Reactive Power Limits-Seasonal Variations



3.2 Island Link-Soldiers Pond Converter Station

The variations in reactive power limits for the Soldiers Pond converter station are shown in Figure 3-6.

It can be seen that the margin between the upper and lower reactive limits is fairly constant over the whole range of dc power for each season. The following approximate average margins were observed between the upper and lower reactive limits:

Table 3-2: Soldiers Pond Reactive Power Margins

Season/ Load Level	Margin (upper-lower)-MVAr
Winter/Peak	220
Spring-Fall/Intermediate	210
Summer Day/Light	210
Summer Night/Extreme Light	215

There is little variation in the margin over the different seasons. The margin at Soldiers Pond is seen to be significantly lower (less than 40%) than the margin at Muskrat Falls. The minimum value of 210 MVAr from above represents 23% of the rated dc power of 900 MW. During the winter peak season, the reactive limits of the system differ widely between the condition when the ML is either exporting power or importing power.

As seen in Figure 3-7, there are significant variations in the absolute values of the limits in different seasons. Under extreme light load conditions, the system is unable to absorb any reactive power and must provide at least 50 MVAr to the converter to maintain the voltage below 105%.

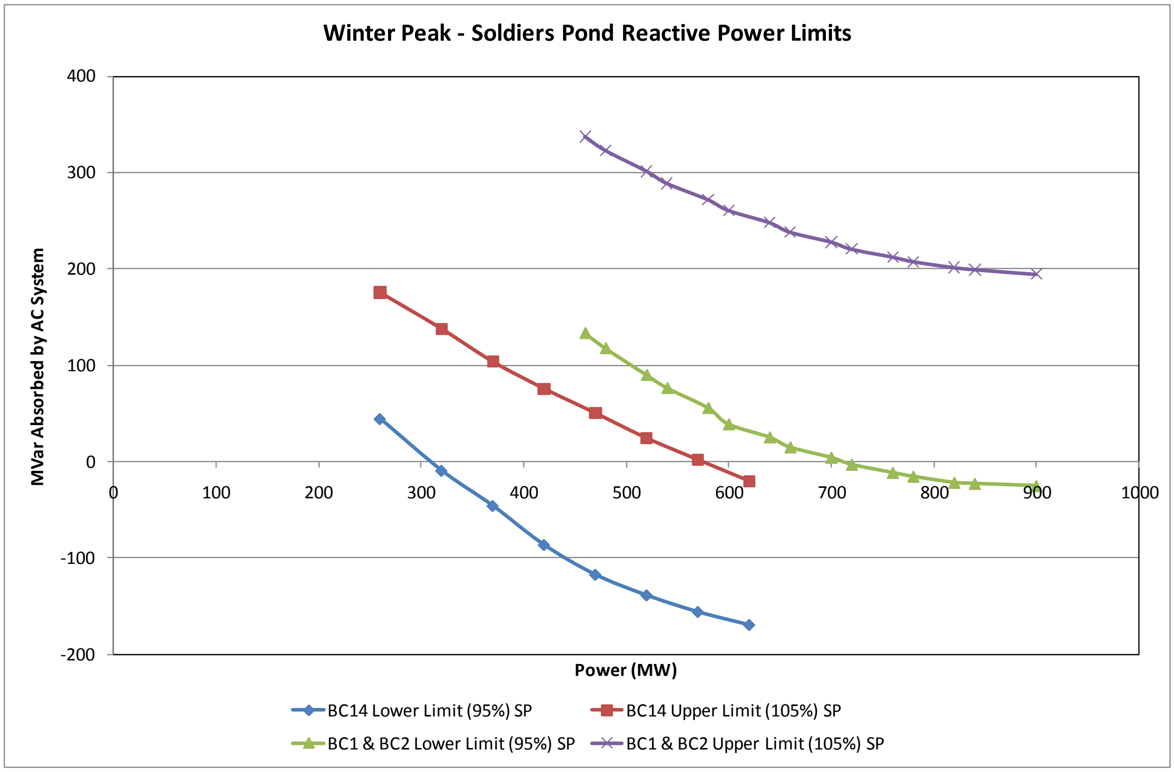
It would appear, therefore that at Soldiers Pond it will not be possible to use a single composite reactive power limit for all seasons or all system conditions and that a flexible reactive management system will be required at this converter station.

An illustrative example of a reactive power management scheme is shown in Figure 3-8. This figure shows the ac system upper and lower reactive limits, the converter reactive power requirements (assumed to be 50% of the dc power), the net reactive power requirements using filters (equal to 50% of the converter reactive requirement, switched in three stages depending on the dc power level) and the final reactive power requirement when an adjustable 200 MVAr reactive source (switched capacitors, SVC, or synchronous condenser) is added at the converter bus. The converter reactive power requirement is well below the system lower limit over the whole range of dc power. The addition of the switched filters brings the net reactive closer to the lower limit but there are still dc power levels at which the operating point is outside the system limits. The addition of an adjustable reactive power source can bring the operating point within the system capabilities over the complete range of dc power. In this example, the additional reactive source was taken as 200 MVAr and was adjusted according to the dc power level in the following manner:

DC Power(MW)	Reactive Support(MVAr)
900	200
800	150
700	100
600	100
500	100
270	100
200	150
160	175
130	200
110	200

It is emphasized that this example is purely illustrative and does not represent any suggested or recommended scheme for reactive power management.

Figure 3-6: Soldiers Pond Reactive Power Limits



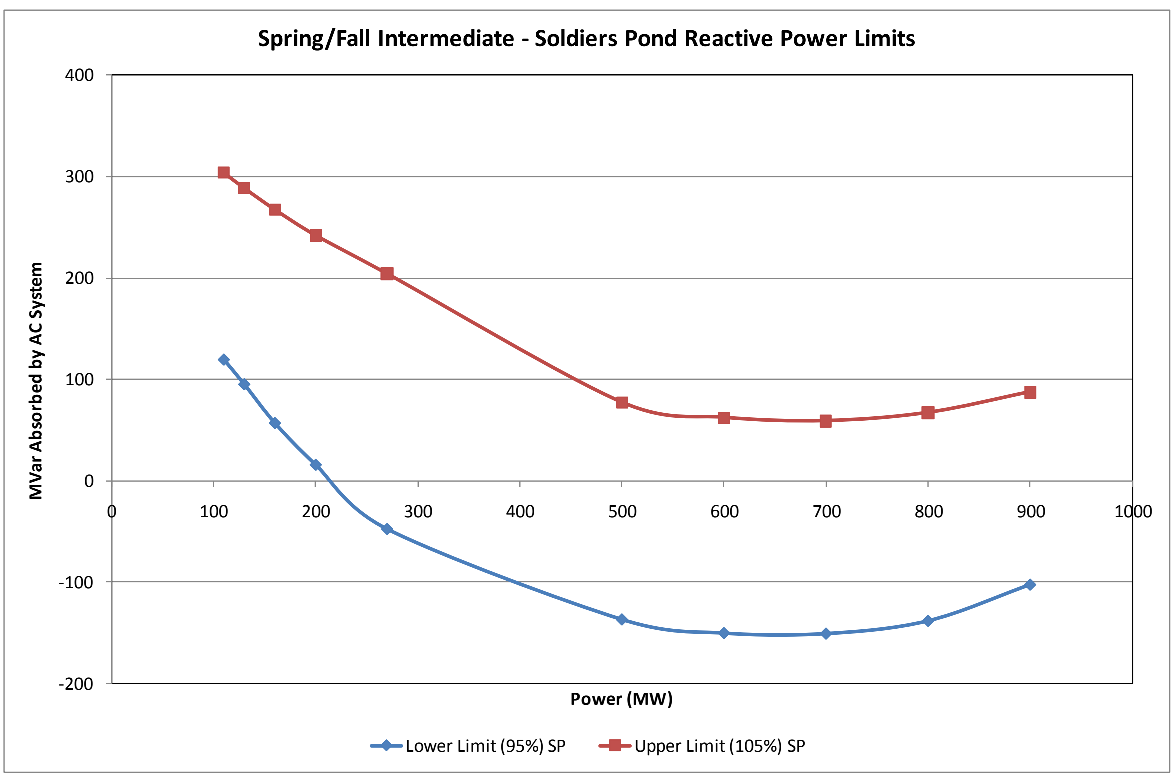
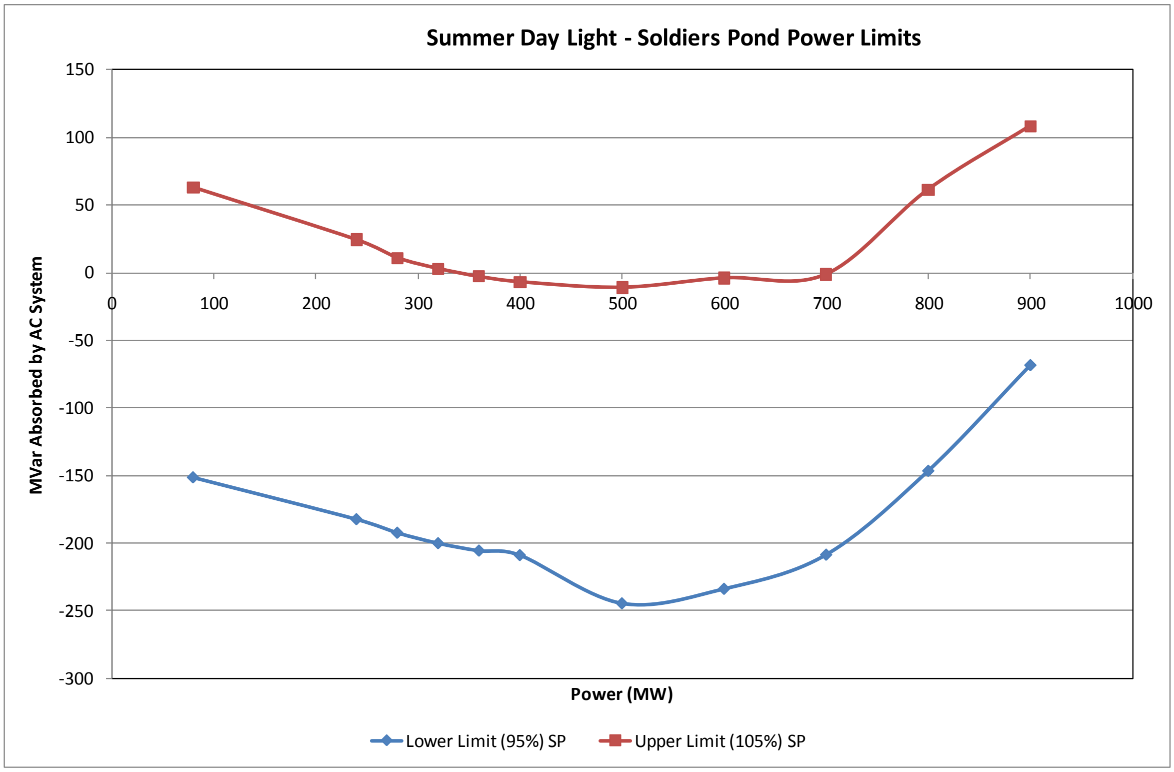


Figure 3-6: Soldiers Pond Reactive Power Limits



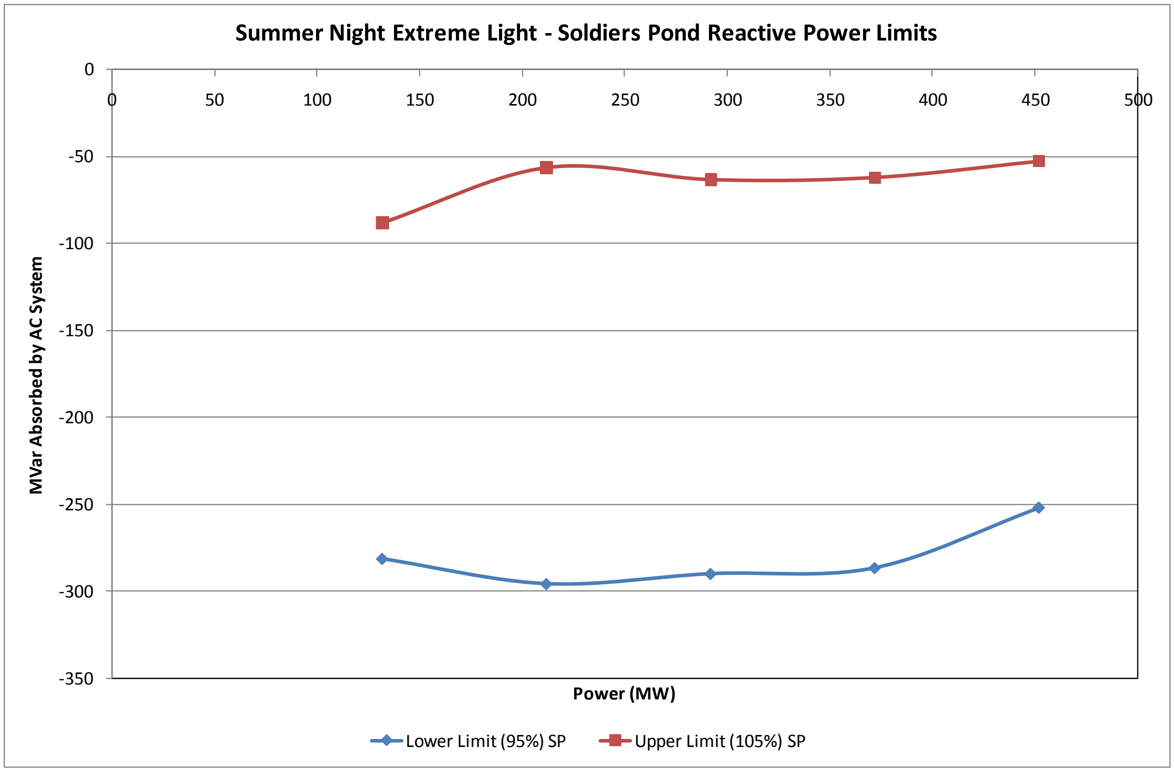


Figure 3-7: Soldiers Pond Reactive Power Limits-Seasonal Variations

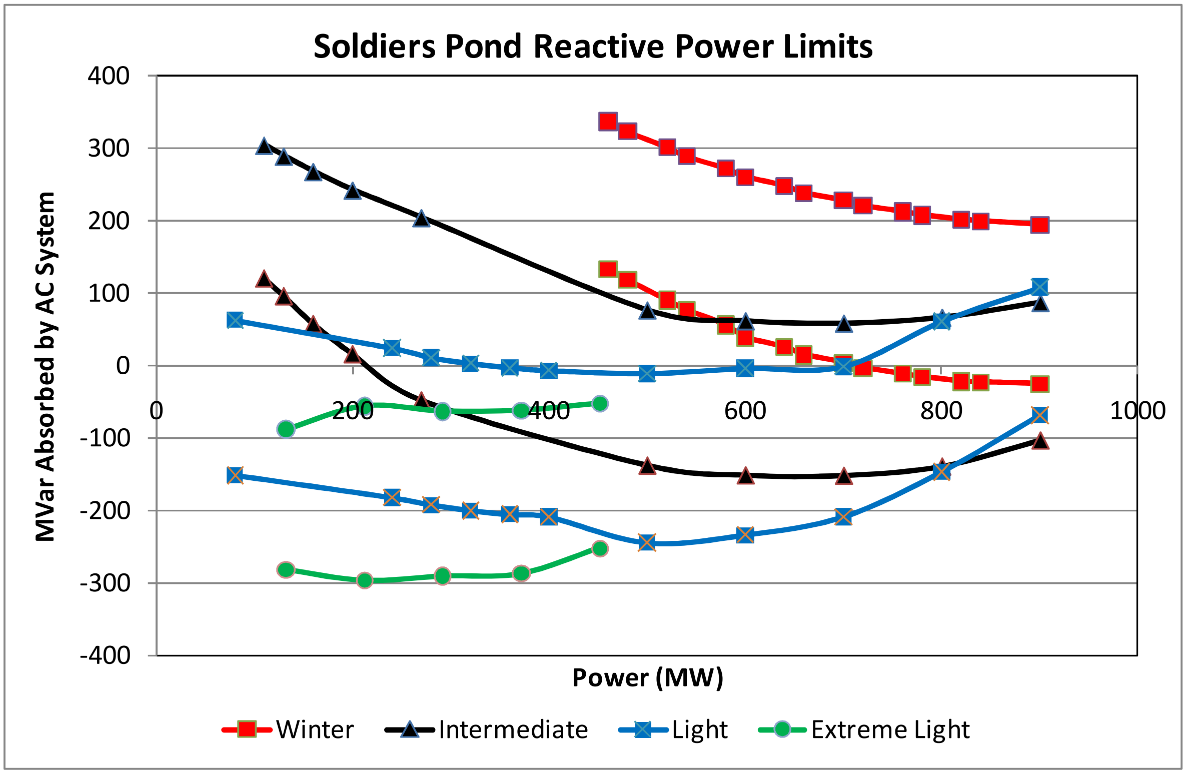
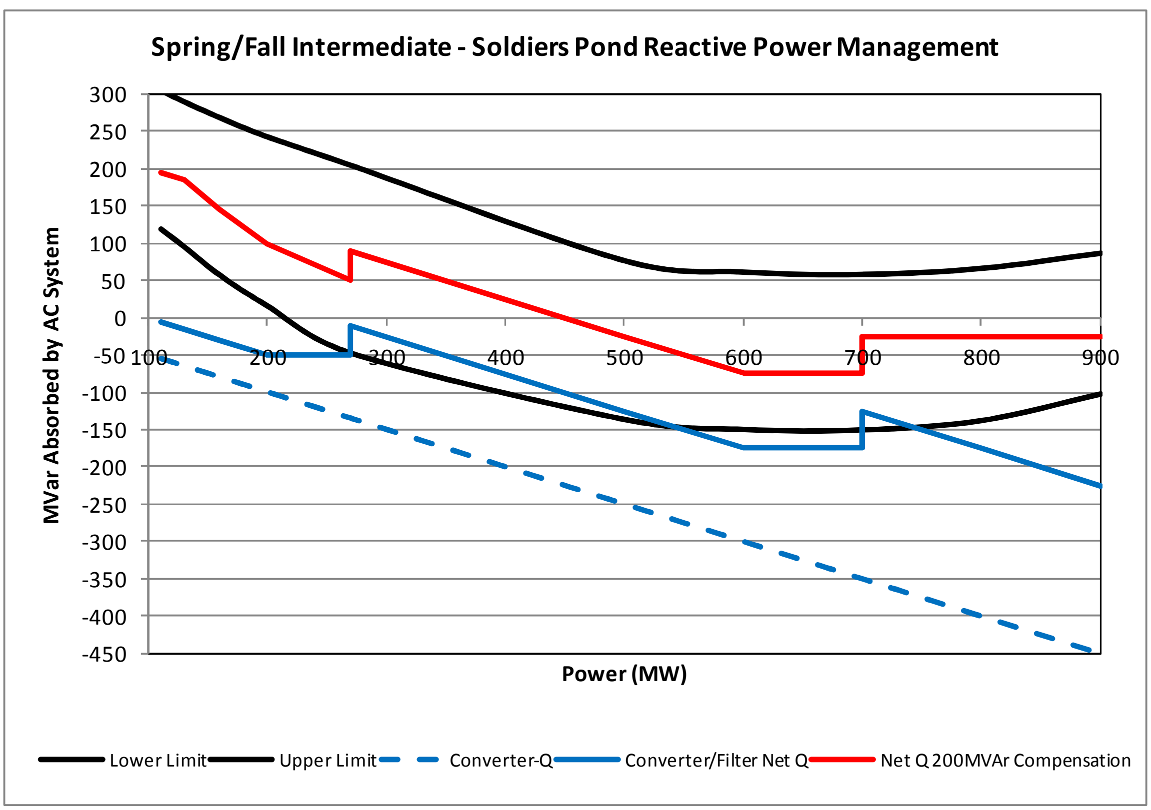


Figure 3-8: Soldiers Pond Reactive Power Management



3.3 Maritime Link-Bottom Brook Converter Station

The variations in reactive power limits for the Bottom Brook converter station are shown in Figure 3-9.

It can be seen that the margin between the upper and lower reactive limits is fairly constant over the whole range of dc power for each season. The following approximate average margins were observed between the upper and lower reactive limits:

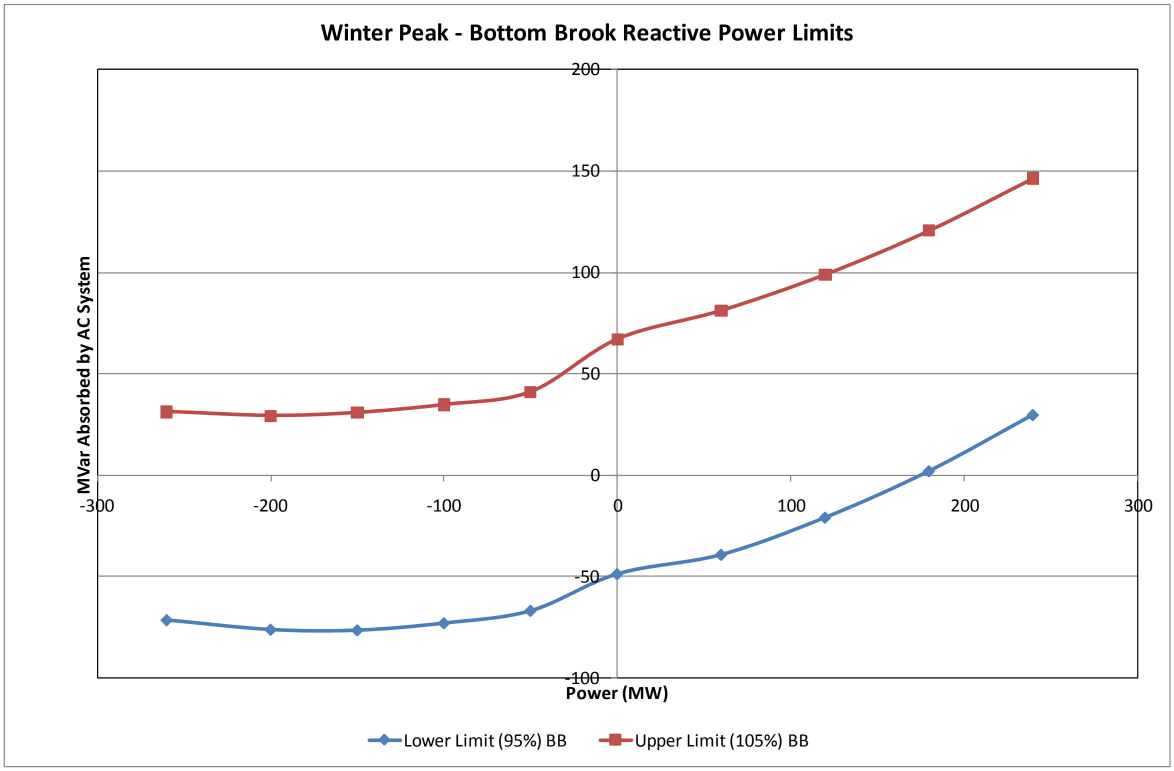
Table 3-3: Bottom Brook Reactive Power Margins

Season/ Load Level	Margin (upper-lower)-MVAr
Winter/Peak	110
Spring-Fall/Intermediate	120
Summer Day/Light	100
Summer Night/Extreme Light	80

There is little variation in the margin over the different seasons except for the extreme light load condition. The margin at Bottom Brook is seen to be much smaller than the margin at either Muskrat Falls or Soldiers Pond. The minimum value of 80 MVAr from above represents 16% of the rated converter power of 500 MW.

As seen in Figure 3-10, there is a significant variation in the absolute values of the reactive power limits in different seasons. As with Soldiers Pond, this would suggest the need for a flexible reactive power management scheme.

Figure 3-9: Bottom Brook Reactive Power Limits



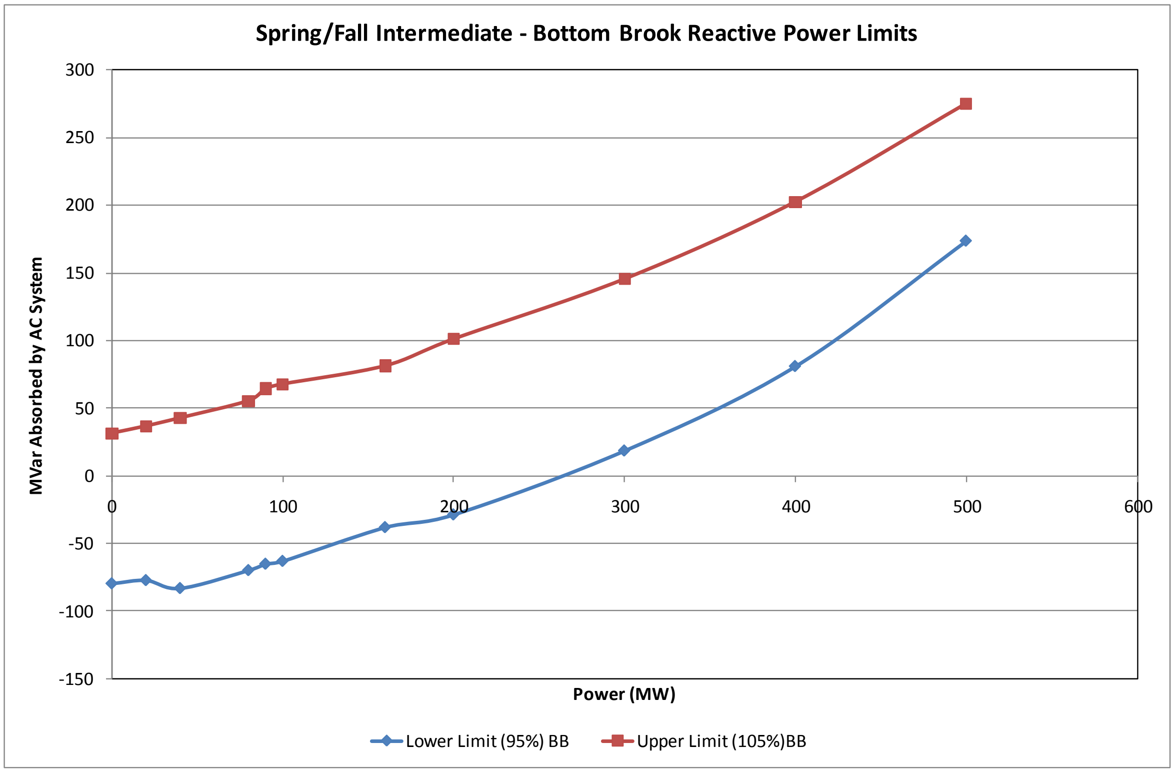
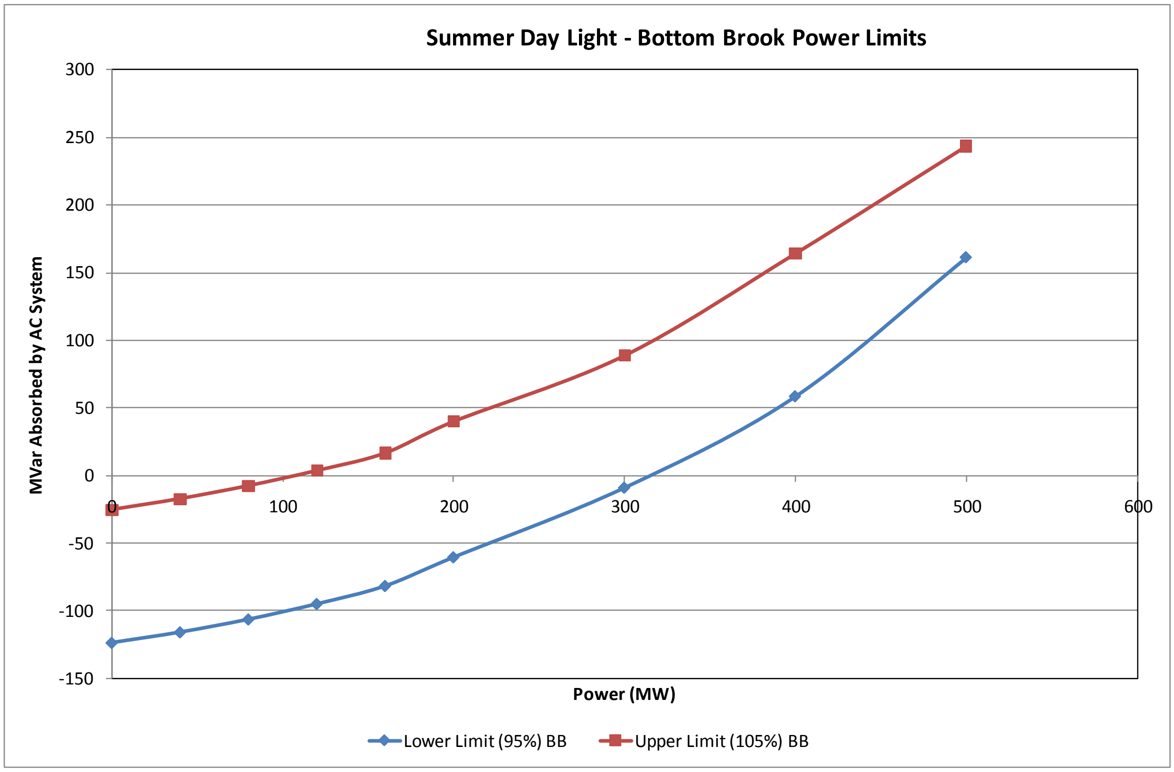


Figure 3-9: Bottom Brook Reactive Power Limits



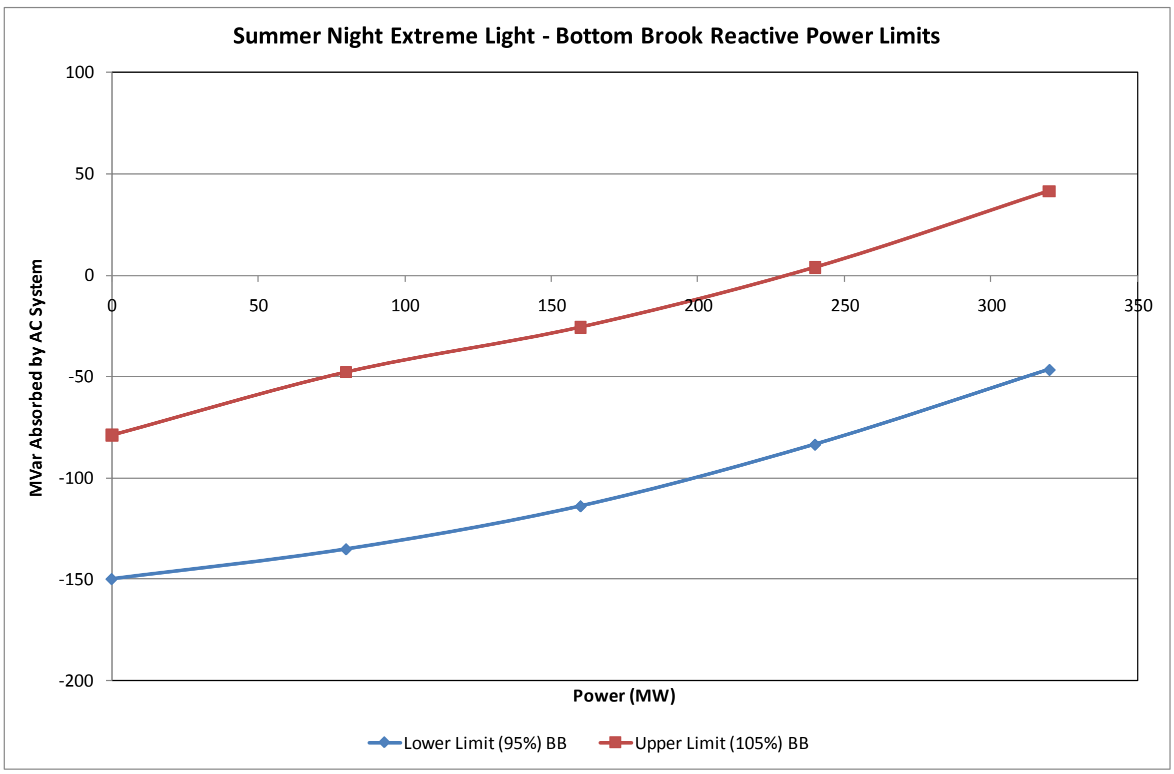
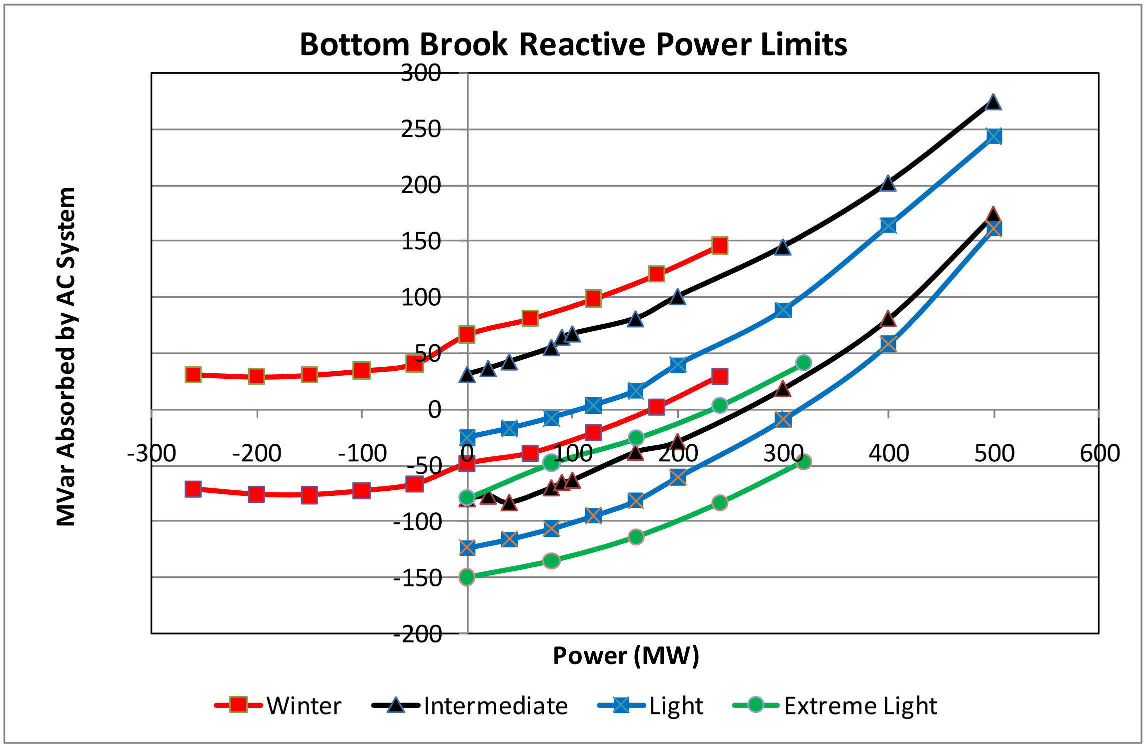


Figure 3-10: Bottom Brook Reactive Power Limits-Seasonal Variations



4 CONCLUSIONS

The reactive power capability of the ac systems at Muskrat Falls, Soldiers Pond and Bottom Brook were determined from the normal system condition voltage limits of ±5% of nominal voltage. These results are based on the present system definition and configuration. Subsequent stability studies and/or modifications to the system configuration may alter these limits significantly. Although the reactive limits developed in this study are suitable for use by manufacturers in preparing comparable bids for converter stations, these limits will need to be re-calculated by the selected converter manufacturer at the design stage, using the latest available system information so that adequate reactive power management strategies can be developed by the converter manufacturer using the actual converter characteristics and filter arrangements.

4.1 Island Link-Muskrat Falls Converter Station

The ac system supplying the Muskrat Falls converter station is relatively strong and has ample reactive power capability to absorb approximately 150 MVAr and supply approximately 400 MVAr of reactive power over the complete range of converter power levels. As an example of this, under Scenario BC-1 (see Figure A-1 in Appendix-A), the ac system is supplying a total of 132 MVAr. Of this total, 70 MVAr is supplied by the three units at Muskrat Falls (133 MVAr at the generator voltage level) and 62 MVAr is supplied by the 2x315 kV lines connected to the Muskrat Falls tap substation. At Churchill Falls 315 kV, the total reactive power being sent to Churchill Falls is 81 MVAr, indicating that the all of the reactive power being supplied in addition to the generators at Muskrat Falls is being produced by the 315 kV lines between Churchill Falls and Muskrat Falls.

The margin between the upper and lower reactive power limits of the ac system is approximately 570 MVAr which represents 63% of the rated dc power of 900 MW. There is little variation in the reactive power limits over the different seasons and load levels. This should allow the use of a single composite reactive power management scheme for all load conditions. It can be concluded that no additional reactive power source is required at Muskrat Falls.

4.2 Island Link-Soldiers Pond Converter Station

The ac system at Soldiers Pond is not as strong as that at Muskrat Falls and for the normal operating situation (LIL providing power to the Island, the ML exporting power to Nova Scotia), under winter peak load conditions, the ac system can provide virtually no reactive power to the converter station although the system can absorb between 200-300 MVAr depending on the dc power level. The situation improves with lower load levels. For intermediate load levels, the ac system can provide 100-150 MVAr of reactive power over the upper part of the dc power range while being able to absorb less than 100 MVAr over the same range. For light load levels, the ac system can provide between 50-250 MVAr and for the extreme light load level, the ac system can provide between 250-300 MVAr of reactive power. The system absorption capability is very limited or less than zero for both these load levels. The margin between the upper and lower reactive power limits of the ac system is approximately 210 MVAr which represents 23% of the rated dc power of 900 MW.

The significant variations in the reactive power limits over the different seasons and load levels suggests that a flexible reactive power management scheme will be required at Soldiers Pond to cater to this wide variation in reactive power capabilities.

With the addition of a +300/-180 MVAr of high-inertia synchronous condenser at Soldiers Pond 230 kV, the ac system limits calculated in this report will be increased by the rating of the synchronous condenser. The upper limit curves (absorption) will move in the positive direction by 180 MVAr and the lower limit curves will move in the negative direction by 300 MVAr over the whole range of power levels. This adds 480 MVAr to the margin between the upper and lower limits.

4.3 Maritime Link-Bottom Brook Converter Station

The ac system at Bottom Brook is the weakest of the three examined. Above an export level of 250 MW, the ac system is unable to provide any reactive power except under extreme light load conditions. At lower export levels, for winter peak and intermediate load levels, the reactive support capability of the system only reaches approximately 50 MVAr. The margin between the upper and lower reactive power limits of the ac system is approximately 80 MVAr which represents 16% of the rated dc power of 500 MW.

The significant variations in the reactive power limits over the different seasons and load levels suggests that a flexible reactive power management scheme will be required at Bottom Brook to cater to this wide variation in reactive power capabilities.

The use of VSC technology for the Bottom Brook converter would enable the converter to produce and absorb reactive power. Typically, VSC converters can absorb or produce reactive power at a value equal to 50% of the rated dc power. Thus 2x250 MW converters could absorb/produce up to 250 MVAr of reactive power, increasing the margin between the upper and lower limits by 500 MVAr.

APPENDIX A

BASE CASE LOAD FLOWS

LIST OF FIGURES

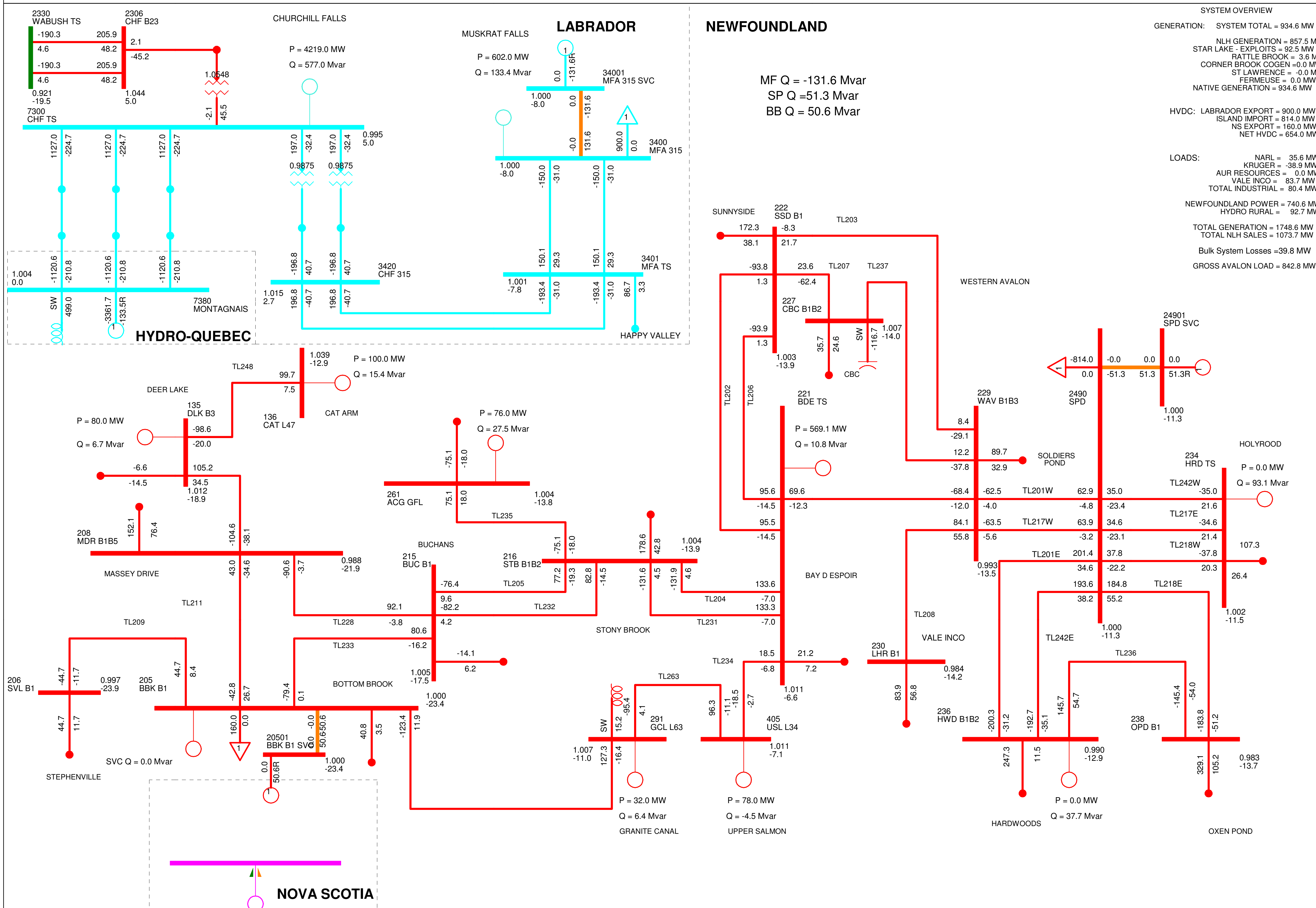
Note: The sign convention used in the load flow plots is:

- Positive flows (P and Q) are from the bus and generator, and
- Negative flows (P and Q) are toward the bus and generator.

Figure A- 1

BC-1 Winter Peak 2017/ Island Link @ 900MW/ Maritime Link @ 158MW/ Economic Dispatch/3 units @ Muskrat Falls

BC1 -2017 PEAK - NLH SYS LOAD 1552MW, 814MW IMP, 158MW EXP
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:26



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

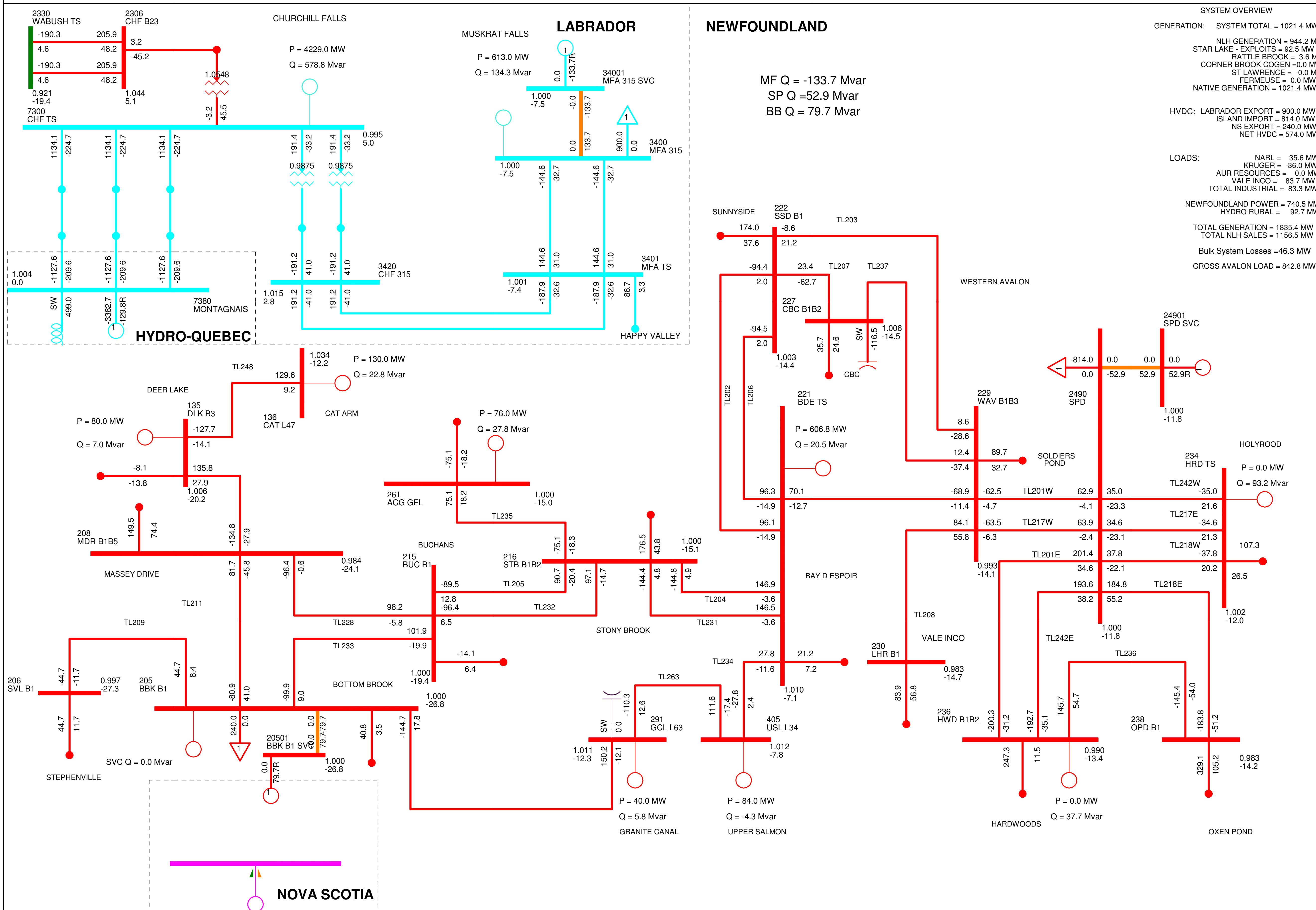
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 2

BC-2 Winter Peak 2017/ Island Link @ 900MW/ Maritime Link @ 239MW/ Maximum Dispatch/3 units @ Muskrat Falls

BC2 -2017 PEAK - NLH SYS LOAD 1552MW, 814MW IMP, 239MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:26



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

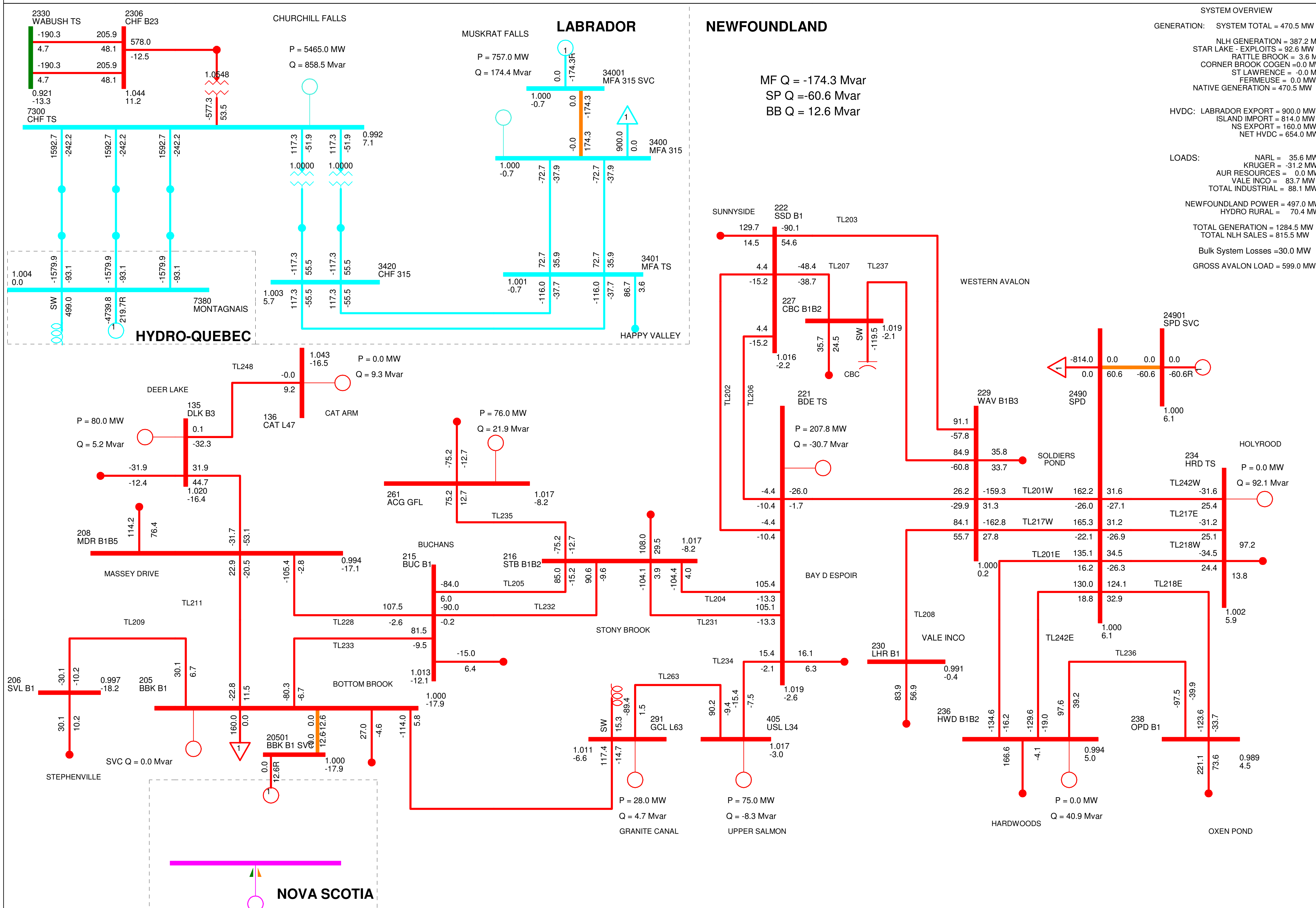
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 3

BC-5 Intermediate 2017/ Island Link @ 900MW/ Maritime Link @ 158MW/ Economic Dispatch

BC5 -2017 INTR - NLH SYS LOAD 1100MW, 814MW IMP, 158MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:27



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

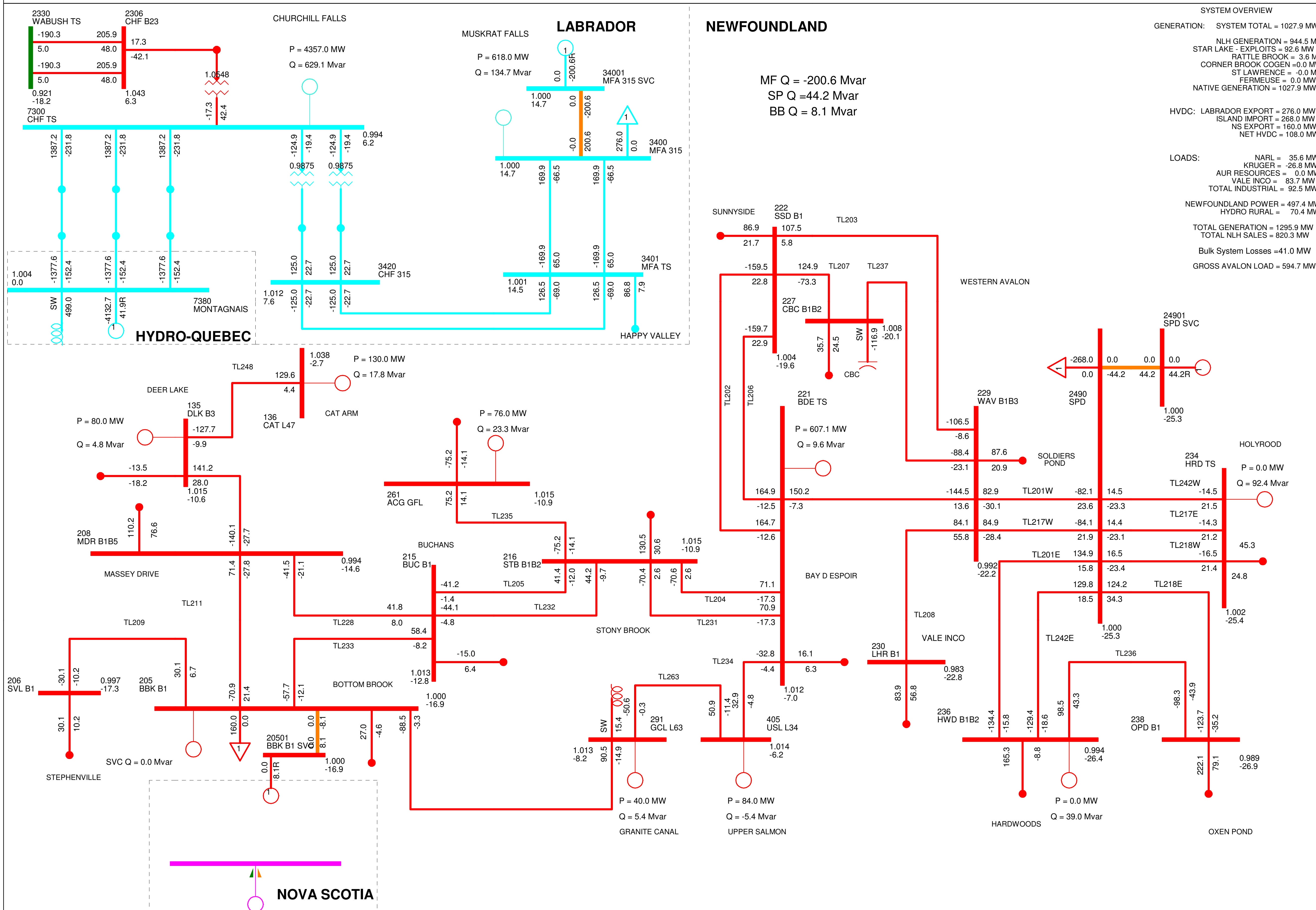
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 4

BC-6 Intermediate 2017/ Island Link @ 276MW/ Maritime Link @ 158MW/ Maximum Dispatch

BC6 -2017 INTR - NLH SYS LOAD 1100MW, 268MW IMP, 158MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:27



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

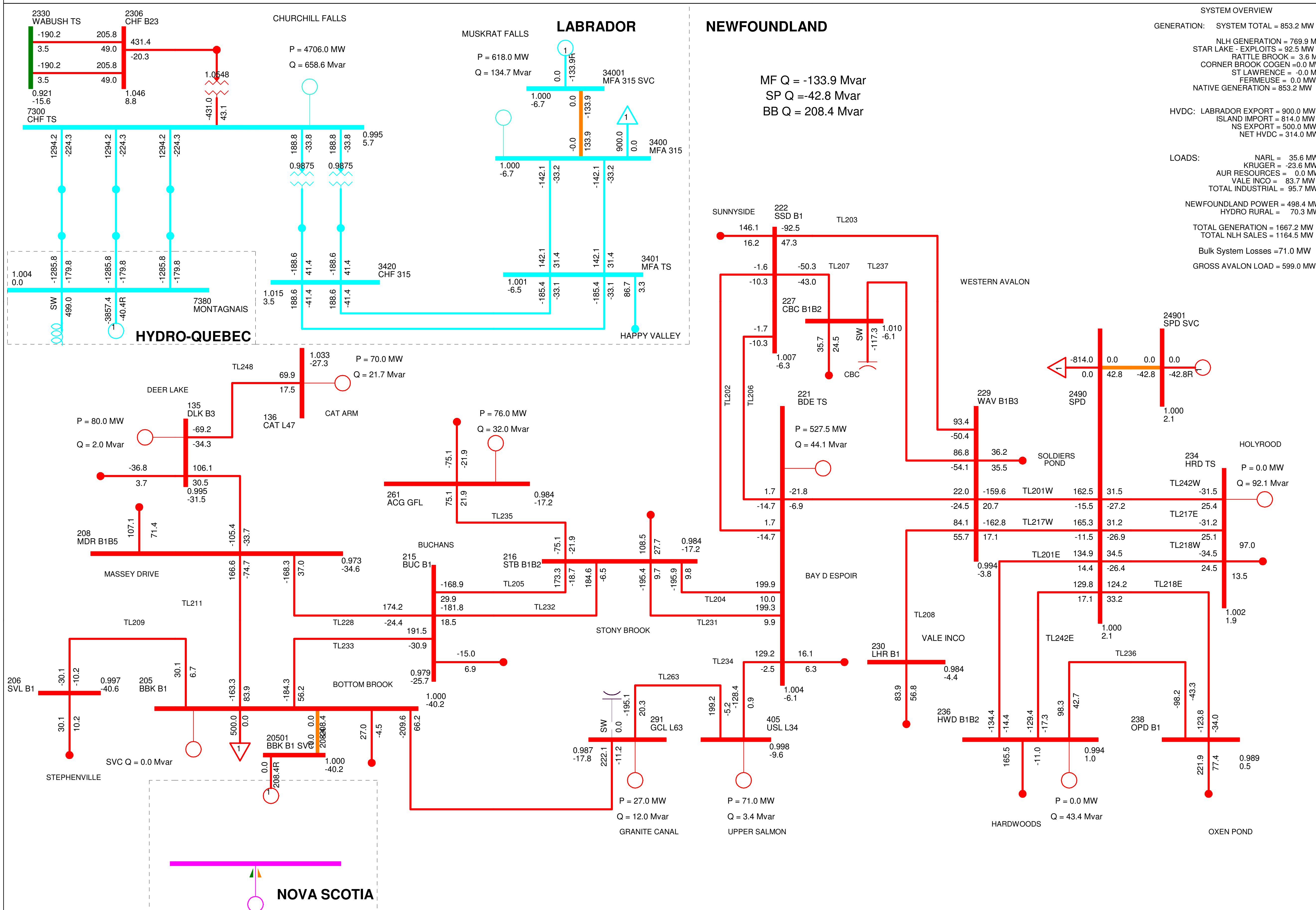
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 5

BC-7 Intermediate 2017/ Island Link @ 900MW/ Maritime Link @ 500MW/ Economic Dispatch

BC7 -2017 INTR - NLH SYS LOAD 1100MW, 814MW IMP, 500MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:28



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

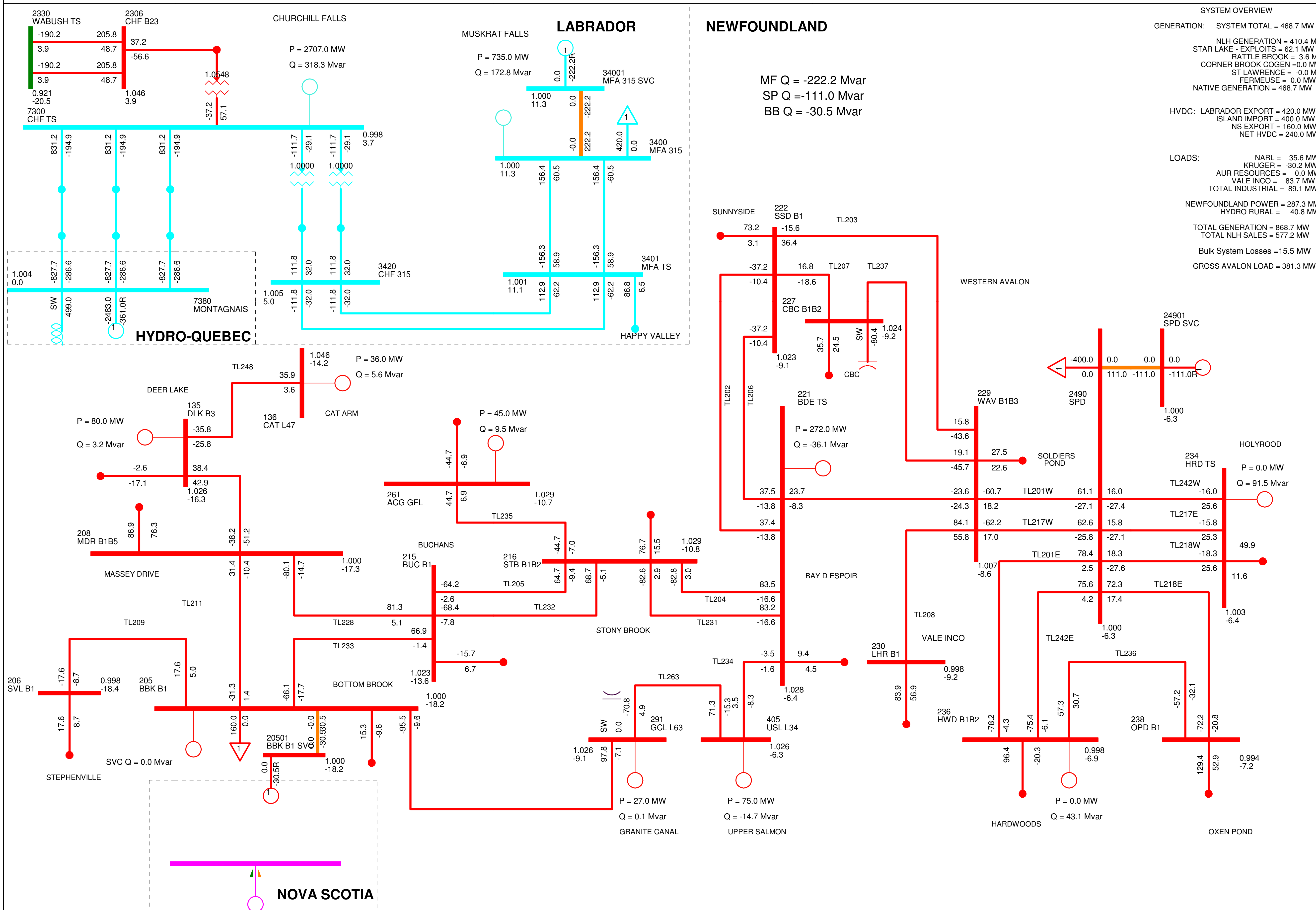
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 6

BC-8 Light 2017/ Island Link @ 420MW/ Maritime Link @ 158MW/ Minimum Dispatch

BC8 -2017 LIGHT - NLH SYS LOAD 700MW, 400MW IMP, 158MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:29



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

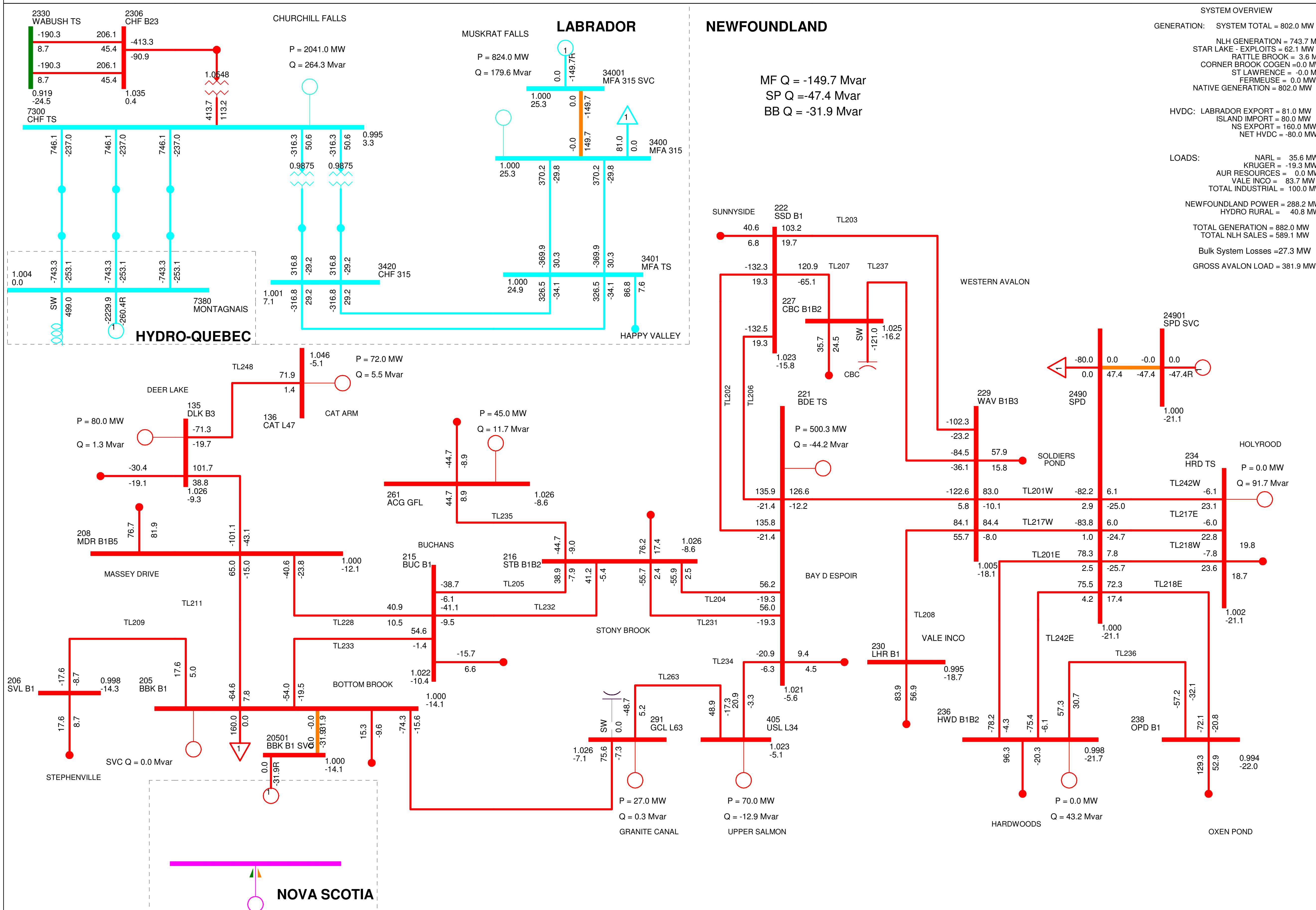
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 7

BC-9 Light 2017/ Island Link @ 81MW/ Maritime Link @ 158MW/ Economic Dispatch

BC9 -2017 LIGHT - NLH SYS LOAD 700MW, 80MW IMP, 158MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:30



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

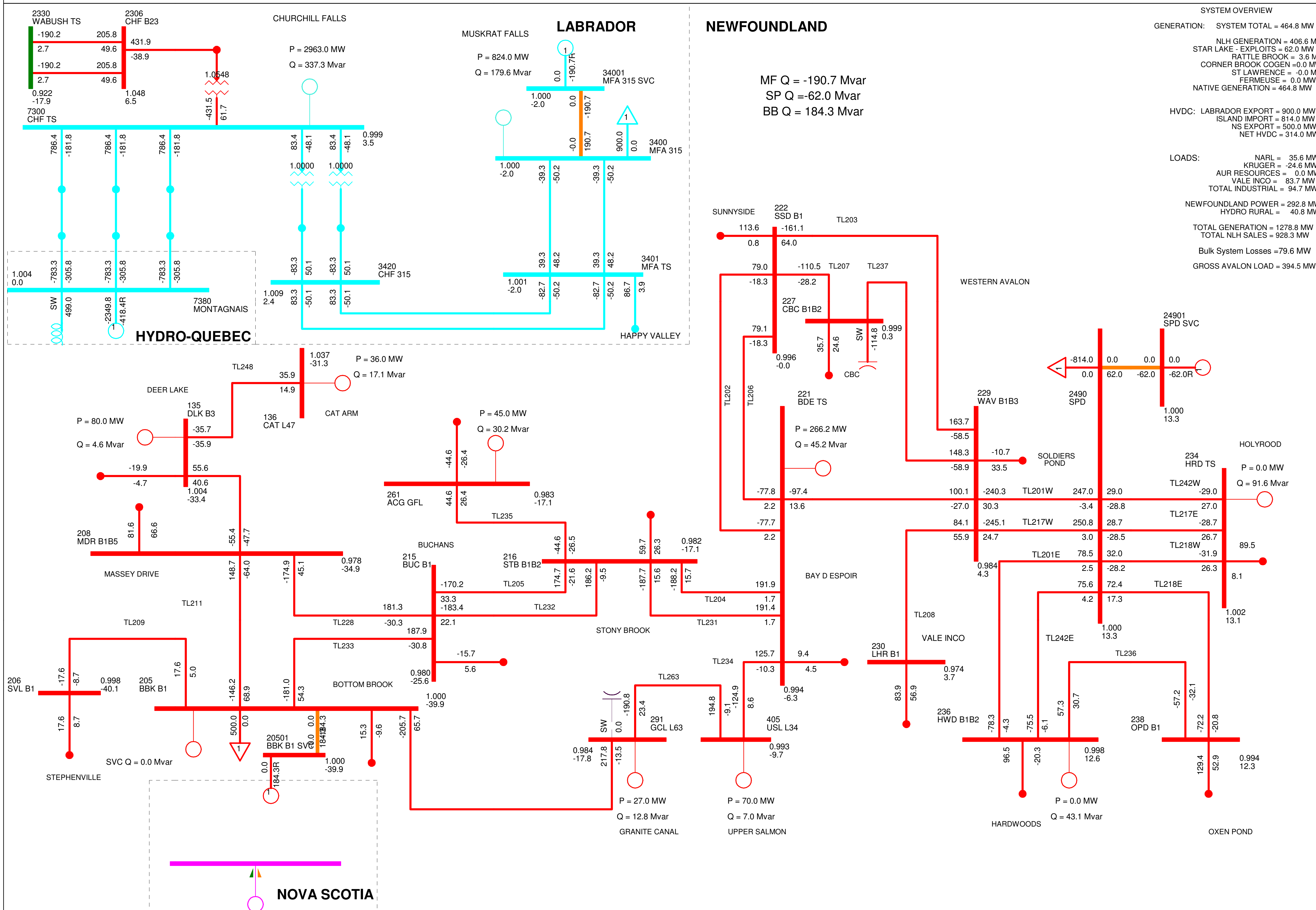
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 8

BC-10 Light 2017/ Island Link @ 900MW/ Maritime Link @ 500MW/ Economic Dispatch

BC10 -2017 LIGHT - NLH SYS LOAD 700MW, 814MW IMP, 500MW EX
LABRADOR MODEL INCLUDED
TUE, DEC 06 2011 13:31



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

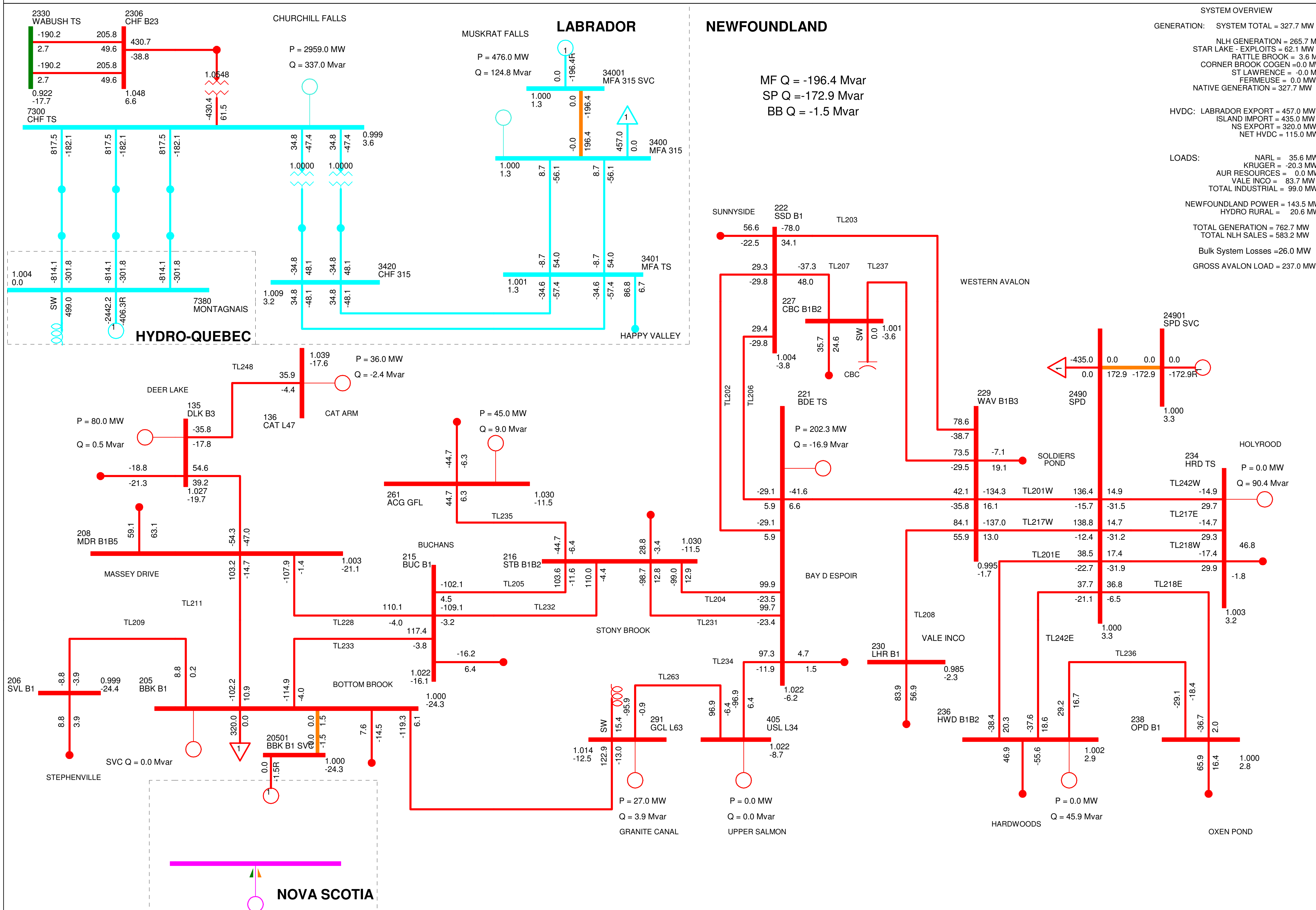
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 9

BC-13 Extreme Light 2017/ Island Link @ 457MW/ Maritime Link @ 320MW/ Minimum Dispatch

BC13 -2017 ELIGHT - NLH SYS LOAD 420MW, 435MW IMP, 320MW EX
RPS-BC13 EXTREME LIGHT
TUE, DEC 06 2011 13:32



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

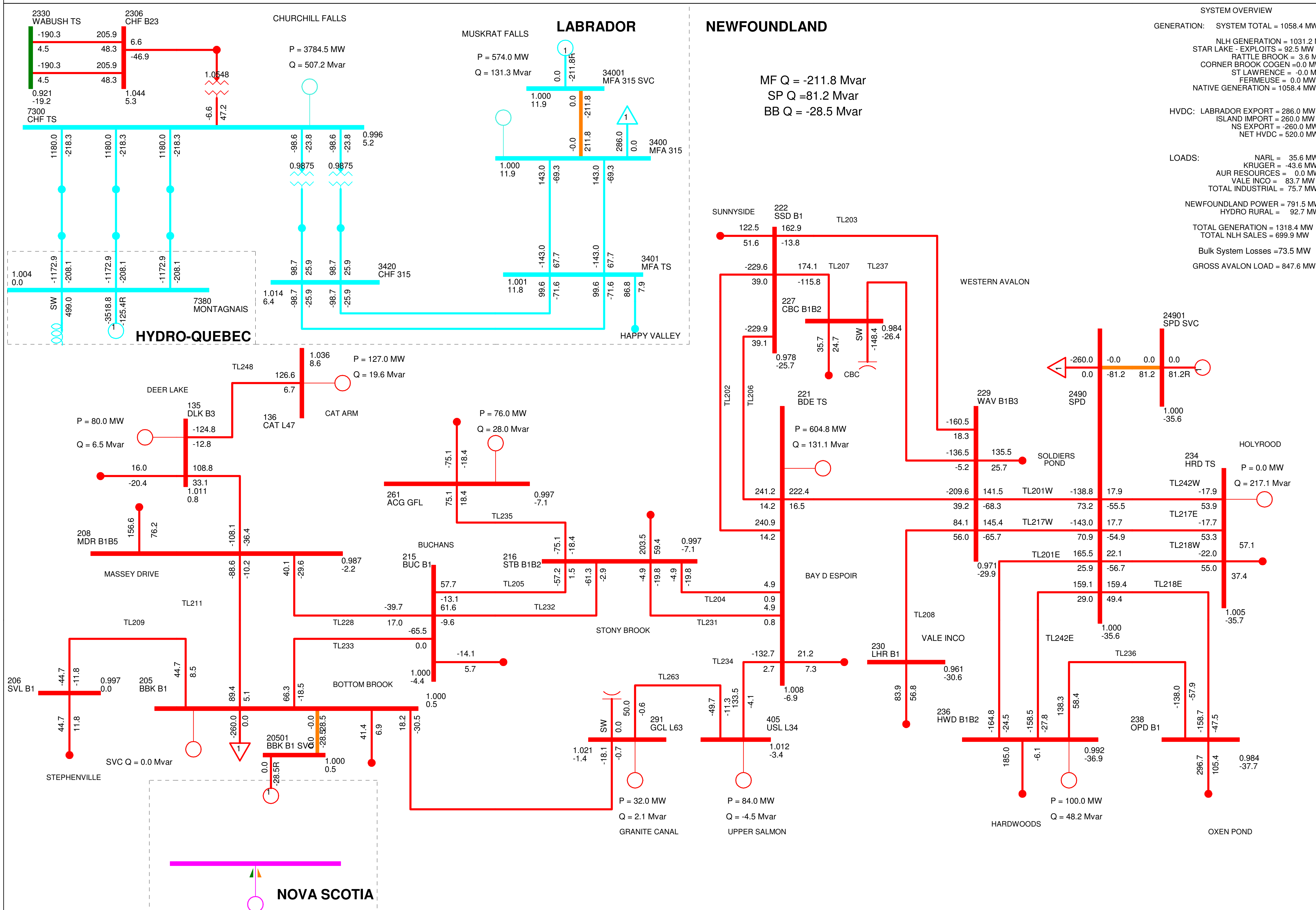
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Bipolar operation of NL-LAB HVDC
- Generation: Economic dispatch

Figure A- 10

BC-14 Winter Peak 2017/ Island Link @ 286MW Monopole/ Maritime Link @ -260MW/ Maximum Dispatch

BC14 -2017 PEAK - NLH SYS LOAD 1552MW, 260MW IMP, -260 EXP
LABRADOR MODEL INCLUDED - MONOPOLE METALLIC RETURN
TUE, DEC 06 2011 13:33



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Generation: Economic dispatch
- Bipolar operation of NL-LAB HVDC

SNC•LAVALIN

nalcor energy

Lower Churchill Project

STABILITY STUDIES

SLI Document No.: 505573-480A-47ER-0004-01

Nalcor Reference No.: ILK-SN-CD-8000-EL-RP-0001-01-B2

Date: 06-Mar-2012

Prepared by: M Ch
Mohamed El Chehaly

Verified by: PAnderson
Peter Anderson

Approved by: Satish Sud
Satish Sud

REGISTERED PROFESSIONAL ENGINEER
PEG Newfoundland and Labrador
SATISH SUD
Satish Sud
SIGNATURE
6-MAR-2012
DATE
NEWFOUNDLAND & LABRADOR

Revision					Remarks
N°	By	Verif.	Appr.	Date	
01	MEC	PA	SS	06-Mar-2012	Re-Issued for use
00	MEC	PA	SS	07-Dec-2011	Issued for use

TABLE OF CONTENTS

Page No.

List of Figures

List of Tables

NLH Index of Terminal Station Names

Location	ID	Location	ID
Barachoix	BCX	Holyrood	HRD
Bay d'Espoir	BDE	Howley	HLY
Bay L'Argent	BLA	Indian River	IRV
Bear Cove	BCV	Jackson's Arm	JAM
Berry Hill	BHL	Linton Lake	LLK
Bottom Brook	BBK	Long Harbour	LHR
Bottom Waters	BWT	Main Brook	MBK
Buchans	BUC	Massey Drive	MDR
Cat Arm	CAT	Monkstown	MKS
Churchill Falls	CFA	Muskrat Falls	MFA
Come-by-Chance	CBC	Oxen Pond	OPD
Coney Arm	CAM	Paradise River	PRV
Conne River	CRV	Parson's Pond	PPD
Corner Brook Freq. Conv.	CBF	Peter's Barren	PBN
Cow Head	CHD	Plum Point	PPT
Daniels Harbour	DHR	Rattle Brook	RBK
Deer Lake	DLK	Rocky Harbour	RHR
Doyles	DLS	Roddicton Woodchip	RWC
Duck Pond	DPD	Sally's Cove	SCV
English Harbour West	EHW	Soldiers Pond	SPD
Farewell Head	FHD	South Brook	SOK
Glenburnie	GLB	Springdale	SPL
Glenwood	GWD	St.Anthony Airport	STA
Grand Bay	GBY	St.Anthony Diesel Plant	SDP
Grandy Brook	GBK	Star Lake	SLK
Grand Falls Freq. Conv.	GFC	Stephenville	SVL
Granite Canal	GCL	Stony Brook	STB
Hampden	HDN	Sunnyside	SSD
Happy Valley	HVY	Upper Salmon	USL
Hardwoods	HWD	Western Avalon	WAV
Hawkes Bay	HBY	Wiltondale	WDL
Hinds Lake	HLK		

1 INTRODUCTION

1.1 Overview of the System

This Report presents the results of the stability studies carried out to examine the dynamic performance of the ac and dc systems including the HVdc interconnections between Muskrat Falls and Soldiers Pond (Island Link) and between Bottom Brook and the Nova Scotia power system (Maritime Link). The present Design Basis considers, for the Island Link, a dc voltage level of ±350 kV and a nominal bipole rating of 900 MW and, for the Maritime Link, a dc voltage level of ±200 kV and a nominal bipole rating of 500 MW. This is interpreted to mean that these rated power levels and rated voltages apply at the rectifier ends (Muskrat Falls and Bottom Brook).

The Island Link will be essentially uni-directional from Labrador to Newfoundland, although there will be nothing in the design of the link to prevent operation in the reverse direction. The Maritime Link is required to have a 500 MW continuous capability in bipolar mode in both directions.

Figure 1-1 provides an overview of the areas considered in these studies. The connection to the Hydro-Quebec (TransEnergie) 735 kV system was represented by a simple equivalent at the Montagnais Substation. The Emera system in Nova Scotia was represented by a simple equivalent at the inverter station of the Maritime Link. The ac system between Churchill Falls and Muskrat Falls and the Island ac system were modelled in detail.

Starting from the base case scenarios provided by Nalcor Energy (Nalcor), the present studies are designed to determine the dynamic performance of the ac/dc systems following major faults on either the ac or dc systems. The faults considered result in the outage of a single element in either the ac or dc system. Because of the relative importance of the Island Link in the overall supply capability of the Island load, the temporary loss of both poles of the Island Link bipole was also considered.

Figure 1-1: Project Area Map

SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	3

Figure 1-2: Provincial Transmission Grid

1.2 Objectives of the Studies

The stability studies were designed to achieve the following objectives:

- To verify that the interconnected systems of Newfoundland and Labrador with interconnections into Quebec and Nova Scotia can operate satisfactorily through a wide range of faults resulting in outages on the transmission network,

- To determine the requirements in terms of control functions that will be required on the Island and Maritime dc links,

- To determine the requirements for additional equipment, in the form of static var compensators and/or synchronous condensers, that will be required at or near the converter stations to ensure satisfactory dynamic performance,

- To verify that load shedding on the Island will not occur for the range of fault cases examined, and

- To determine any operating requirements that must be applied to the Island and Maritime dc links to ensure stable operation.

2 STUDY BASIS

Nalcor provided nineteen base case scenarios for examination. These scenarios are presented in Table 2-1. Scenarios BC-14 to BC-17 considered monopole operation of the Island Link. Since these scenarios already represent a single contingency outage on the system, they were not considered as the starting condition for any of the stability studies.

The major additions to the existing (2011) system planned by Nalcor consist of:

- A new 230 kV line from Granite Canal to Bottom Brook (name not yet designated) to strengthen the supply to Bottom Brook and the Western region, and
- A new 230 kV line from Bay d'Espoir to Western Avalon (name not yet designated) to increase system transfer capability and improve system stability.

The 230 kV supply to the Wabush/ Labrador City area in Western Labrador has been identified in Nalcor's five-year plan to require reinforcement to relieve low voltage conditions and improve system stability. As a result, this area was the source of stability problems for all the initial cases considered. Since the plans for this area are still under investigation, the supply to this area was represented as a fixed, lumped load at the Churchill Falls 230 kV bus.

Following the conclusions derived from the *Load Flow and Short-circuit Studies* (Nalcor ILK-SN-CD-8000-EL-SY-0001-01/ SLI 505573-480A-47ER-0003), a +320/-100 MVAr SVC was placed at Bottom Brook in all cases to ensure sufficient reactive power was provided to the system with the connection of the Maritime Link. Any fixed shunts representing reactive compensation were removed and only those representing ac filters were retained.

Load flow studies were carried out for each scenario, considering normal system conditions (all equipment in service) and outage conditions. In addition to pole outages on the Island dc link, the automatic sequential contingency feature of PSS®E was used to examine all single contingency outages on the ac systems. The results of these load flow studies were presented in the *Load Flow and Short-circuit Studies* report (Nalcor ILK-SN-CD-8000-EL-SY-0001-01/ SLI 505573-480A-47ER-0003) and are not repeated here. However, for each stability study carried out, the base case load flows, showing the initial network conditions, are included in Appendix A.

2.1 Study Criteria

The criteria generally used to carry out stability studies are taken from the NLH Transmission Planning Manual and are summarized below.

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

The above criteria have been in general use for Newfoundland and Labrador Hydro (NLH). Once commissioned, the Island Link will bring 900 MW from Muskrat Falls to Soldiers Pond with a delivered capacity of approximately 814 MW, allowing for losses on the nearly 1,100 km long link. Of this delivered power to the Island it is planned to export 158 MW over the Maritime Link while maintaining an economic dispatch of the Island generation. Under maximum Island dispatch conditions, the export over the Maritime Link could be increased to 239 MW. In 2017, when the peak Island load is forecast to be 1,552 MW, the net import on the Island Link (814-158=656 MW) will represent approximately 42% of the Island peak load. Given this relatively high level it is considered essential that the Island Link be designed to a very high level of reliability and availability and that the system should remain stable and able to operate without load shedding through the most severe single contingencies. Consequently, the system was studied for a series of permanent pole outages, temporary bipole outages and three-phase faults on the ac system to determine the dynamic performance of the system and to determine the additional equipment that would be required, in terms of dynamic support, to ensure stable performance. Given the above, it was not considered necessary to examine the system performance for a successful single pole re-closure of a single-line-to-ground fault as this is much less severe than a three-phase fault.

Given the above requirements to avoid load shedding on the Island for all system disturbances and in view of the limited spinning reserve that would be available on the Island, it was agreed with Nalcor that, in the event of a system disturbance that would result in a frequency depression, the export to Nova Scotia over the Maritime Link would be reduced to zero as quickly as possible, effectively providing additional spinning reserve to the Island system. In discussions with Emera, the Nova Scotia system would be operated with sufficient spinning reserve to maintain operations through such an event. Following system recovery, the Maritime Link could then be manually re-started at a level consistent with the available capacity from Newfoundland.

The only other modification to the above criteria concerns the post-fault ac system voltage. Inverters are susceptible to commutation failure when the ac voltage changes rapidly. Such failures can occur even for relatively small voltage changes, but the probability of a commutation failure is considered small if the post-fault recovery voltage does not fall below 90% (CIGRE, Document 103, “Causes and Consequences of Commutation Failures”, November 1995). Since the models used in the PSS®E program cannot automatically account for commutation failures, it is necessary to manually track the inverter ac voltage to check for compliance with the voltage criterion. An ac voltage criterion of 90% was therefore applied to the Soldiers Pond 230 kV bus.

The generation dispatch levels for each scenario considered are given in Table 2-2.

Table 2-1: Base Case Scenarios

No.	NLH System Load	NS Export Bottom Brook	Island Import Muskrat Falls/Soldiers Pond	Island Generation	Comments
BC-1	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 3-units @ Muskrat Falls
BC-2	Peak-2017(1552MW)	239MW	900/814MW	Maximum	Winter Peak 3-units @ Muskrat Falls
BC-3	Peak-2017(1552MW)	158MW	798/730MW	Maximum	Winter Peak
BC-4	Peak-2041(1900MW)	0MW	900/814MW	Maximum	Winter Peak
BC-5	Intermediate-2017(1100MW)	158MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-6	Intermediate-2017(1100MW)	158MW	276/268	Maximum	Spring/Fall day
BC-7	Intermediate-2017 (1100MW)	500MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-8	Light (700MW)	158MW	414/400MW	Minimum	Summer day
BC-9	Light (700MW)	158MW	81/80MW	Economic Dispatch	Summer day
BC-10	Light (700MW)	500MW	900/814MW	Economic Dispatch	Summer day
BC-11	Extreme Light (420MW)	0MW	81/80MW	Economic Dispatch	Summer night
BC-12	Extreme Light (420MW)	320MW	81/80MW	Economic Dispatch	Summer night
BC-13	Extreme Light (420MW)	320MW	457/435MW	Minimum	Summer night
BC-14	Peak-2017 (1552MW)	-260MW	286/260MW-Monopole	Maximum	Winter Peak
BC-15	Intermediate-2017(1100MW)	158MW	378/333MW-Monopole	Economic Dispatch	Spring/Fall day
BC-16	Light (700MW)	500MW	638/518MW-Monopole	Minimum	Summer day
BC-17	Extreme Light (420MW)	0MW	215/200MW-Monopole	Minimum	Summer night
BC-18	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls
BC-19	Intermediate-2017(1100MW)	500MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls

Table 2-2: Generation Dispatch Levels

	Unit Size		BC1	BC2	BC3	BC4	BC5	BC6	BC7	BC8	BC9	BC10	BC11	BC12	BC13	BC14	BC15	BC16	BC17	BC18	BC19
	MW	MVA																			
NLH System Load (MW)			1552	1552	1552	1900	1100	1100	1100	700	700	700	420	420	420	1552	1100	700	420	1552	1100
HVDC Export BBK (MW)			158	239	158	0	158	158	500	158	158	500	0	320	320	-260	158	500	0	158	500
Generation Dispatch																					
Churchill Falls Plant	6050	6722	4219	4229	4199	5031	5465	4357	4706	2707	2041	2963	2794	3330	2959	4205	4505	3330	2794	4219	4706
Muskrat Falls Plant	824	916	602	613	618	618	757	618	618	735	824	824	378	415	476	574	618	415	378	824	824
HVDC at Soldiers Pond			815	815	730	815	815	268.5	815	400	80	815	80	80	435	260	333	518	200	815	815
NLH - Hydro																					
Bay d'Espoir Unit 1	76.5	85	70	75	75	75	68	75	65	67	60.5	65.7	67	66	off	75	72	60	61	70	65
Bay d'Espoir Unit 2	76.5	85	70	75	75	75	off	75	65	off	60.5	off	off	66	66	75	72	off	off	70	65
Bay d'Espoir Unit 3	76.5	85	70	75	75	75	68	75	65	67	60.5	65.7	67	66	off	75	72	60	61	70	65
Bay d'Espoir Unit 4	76.5	85	70	75	75	75	off	75	65	off	60.5	off	off	66	off	75	72	60	off	70	65
Bay d'Espoir Unit 5	76.5	85	70	75	75	75	68	75	65	off	60.5	65.7	off	66	off	75	72	60	off	70	65
Bay d'Espoir Unit 6	76.5	85	70	75	75	75	off	75	65	off	60.5	65.7	off	66	off	75	72	60	off	70	65
Bay d'Espoir Unit 7	155	172	145	154	154	154	off	154	135	135	135	off	sc	off	135	154	150	124	sc	145	135
Cat Arm Unit 1	68	75.5	50	65	65	65	sc	65	35	36	36	36	46	39	36	63.5	54	36	36	50	35
Cat Arm Unit 2	68	75.5	50	65	65	65	sc	65	35	sc	36	sc	off	off	off	63.5	54	36	off	50	35
Upper Salmon	84	88.4	78	84	84	84	75	84	71	75	70	70	75	75	off	84	75	70	off	78	71
Hinds Lake	75	83	70	75	75	75	69	75	67	off	67	off	off	69	off	75	69	67	off	70	67
Granite Canal	40.5	45	32	40	40	40	28	40	27	27	27	27	27	30	27	32	28	27	off	32	27
Paradise River	9	10	8	8	8	8	7	8	7	off	7	7	off	7	off	8	7	7	off	8	7
NLH - Thermal																					
Hardwoods GT1/2	57	63.5	sc	sc	sc	45	sc	sc	sc	sc	sc	sc	sc	sc	sc	50	sc	sc	sc	sc	sc
Stephenville GT1	57	63.5	off	off	off	25	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Holyrood Unit 1	175	194.4	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Holyrood Unit 2	175	194.4	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc
Holyrood Unit 3	159	177.2	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc
Holyrood CT1	16	17.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Holyrood CT2	16	17.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NUGS																					
Star Lake			17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4
Rattle Brook			3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
CBP&P			18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Exploits			76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76
Wind																					
St. Lawrence			off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Fermeuse			off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Total Generation			1783	1871	1786	1986	1313	1325	1697	922	936	1333	477	811	814	1405	1317	1300	473	1783	1697

2.2 System Models

In terms of system modelling, the ac system was represented by conventional models common to both steady-state and stability studies. This data was provided by Nalcor in the form of PSS®E data files.

All generators in the system were modelled by their sub-transient, 2-axis models as provided in the PSS®E model library. The data for each generator was provided by Nalcor and is shown in Appendix B. For each generator, Nalcor provided the exciter, stabilizer and governor models as appropriate. These models with their parameters are presented in Appendix B. The system loads were modeled as constant current loads for real power and constant admittance loads for reactive power.

The HVdc links (Island and Maritime) were modelled using the PSS®E library model CDC4T. The details of this model are provided in Appendix B. Both links were modeled as Line Commutated Converters (LCC).

Voltage Source Converters (VSC) are usually associated with dc cables since reclosing is not normally used for dc cable faults. Currently, the only method to clear a fault on the dc circuit is by opening the ac breakers. The duration of the fault clearance is at least 500 ms and can reach up to 1,500 ms. Therefore, ac systems can collapse due to frequency deviation.

Frequency controllers were applied at the Soldiers Pond (inverter) converter and the Bottom Brook (rectifier) converter using the PSS®E library model PAUX1T. The details of this model are provided in Appendix B. The purpose of these frequency controllers is as follows:

- The frequency controller at Bottom Brook was configured to reduce the dc power on the Maritime Link to zero in the event that the frequency at Bottom Brook falls below 60 Hz.

- The frequency controller at Soldiers Pond was configured to increase the dc power on the Island Link in the event that the frequency at Soldiers Pond falls below 60 Hz.

3 RESULTS OF THE STUDIES

3.1 Winter Peak Load Conditions

The forecast peak load on the Island system in 2017-18 is 1,552 MW. The first scenario to be examined under these conditions was BC-2, since this scenario involves the rated transfer across the Island Link (900 MW from Muskrat Falls) and the maximum transfer across the Maritime Link (239 MW from Bottom Brook) under peak load conditions. Figure A-1 in Appendix A shows the load flow of the initial conditions.

The following fault cases were examined:

BC2-ST01: Temporary Bipole Fault on the Island Link

BC2-ST02: Permanent Pole Fault on the Island Link with post-fault mono-polar operation

BC2-ST03: 3-phase/6-cycle fault at Muskrat Falls 315 kV on 315 kV line to Churchill Falls (name not yet designated)

BC2-ST04: 3-phase/6-cycle fault at Bay d'Espoir 230 kV on 230 kV line to Western Avalon (name not yet designated)

BC2-ST05: 3-phase/6-cycle fault at Soldiers Pond 230 kV on 230 kV line to Western Avalon (TL217W)

BC2-ST06: 3-phase/6-cycle fault at Bottom Brook 230 kV on 230 kV line to Granite Canal (name not yet designated)

BC2-ST07: 3-phase/6-cycle fault at Stony Brook 230 kV on 230 kV line to Bay d'Espoir (TL204)

BC2-ST08: 3-phase/6-cycle fault at Bay d'Espoir 230 kV on 230 kV line to Sunnyside (TL202)

BC2-ST09: 3-phase/6-cycle fault at Bay d'Espoir 230 kV with post-fault outage of Bay d'Espoir G7

The dynamic performance of the system is presented in a series of figures for each case showing:

- machine angles,
- ac and dc bus voltages,
- dc power levels,
- active and reactive output of synchronous condensers,
- system frequency.

3.1.1 BC2-ST01: Temporary Bipole Fault on the Island Link

This case represents the condition where a transient fault occurs on both poles of the Island Link. The fault duration was taken as 200 ms (12 cycles), composed of 25 ms (1.5 cycles) to detect the fault and reduce the dc current to zero plus a de-ionization time of 175 ms (10.5 cycles). After this period, the dc power can be ramped back up to any desired value. The ramp rates were selected to result in a ramp-up time to full power of 100 ms (6 cycles), giving a total time from fault initiation to a return to scheduled power of 300 ms (18 cycles).

Previous studies of the use of HVdc to supply the Island load showed a need for additional reactive support and inertia at the Soldiers Pond converter station. The study was therefore carried out with a high-inertia, synchronous condenser connected at Soldiers Pond as shown below (data provided by Hatch report "*DC1210 – HVdc System Sensitivity and VSC Risk Analysis*" based on the Toshiba synchronous condenser).

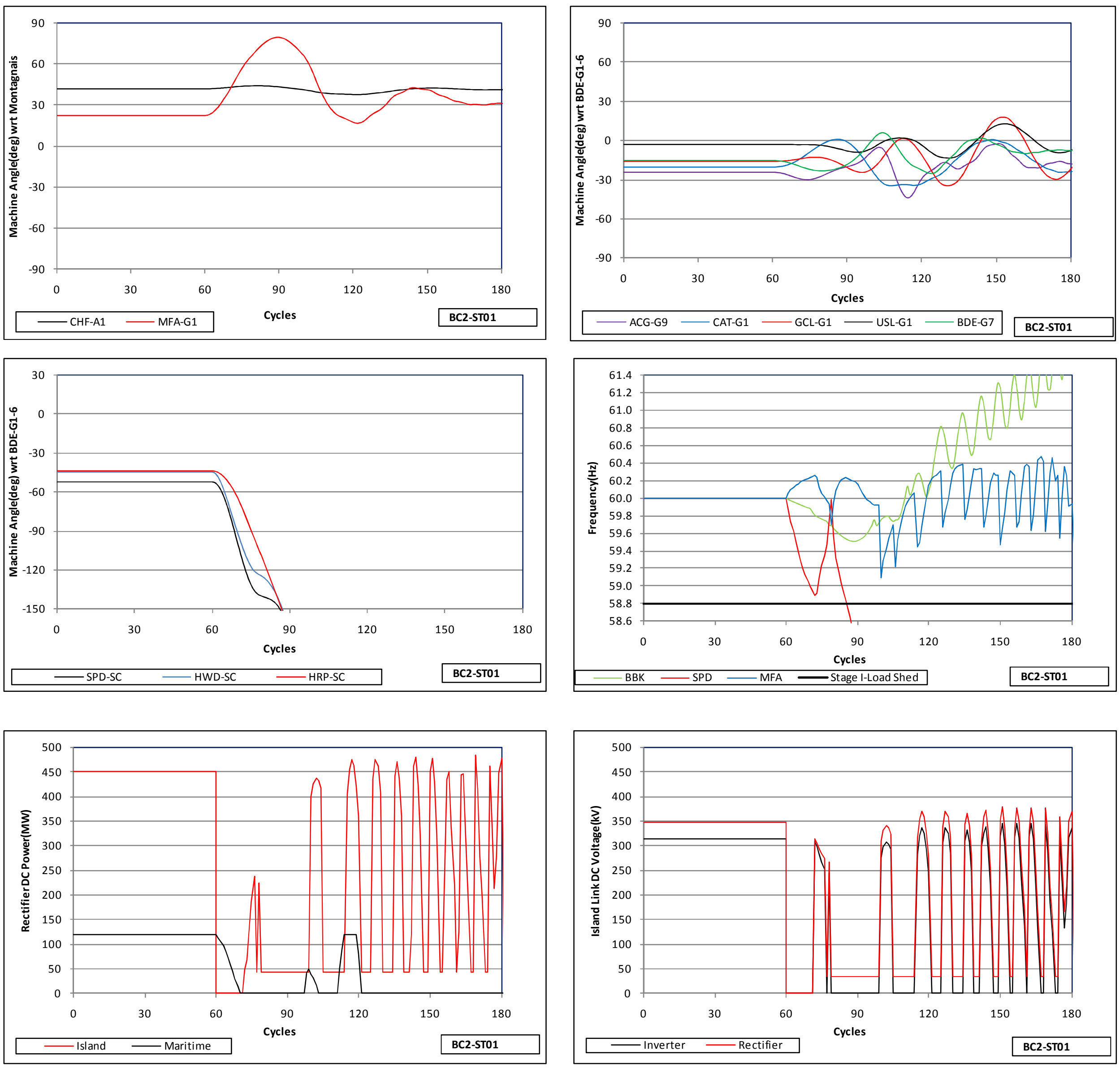
Table 3-1: High-Inertia Synchronous Condenser Data

Parameter	Value	Parameter	Value
Rating	+300/-165 MVAr	Xl	0.09 pu
H	7.84 kW-s/kVA	S(1.0)	0.04
Xd	1.24 pu	S(1.2)	0.14
Xq	0.85 pu	T'd0	11 s
Xd'	0.27 pu	T"d0	0.08 s
Xd"	0.165 pu	T"q0	0.29 s
Xq"	0.177 pu		

For the first case, the above model was scaled to represent a 150 MVAr synchronous condenser.

The results (machine angles, voltages and dc power flow) are shown in Figure 3-1.

Figure 3-1: BC2-ST01, Winter Peak/Island Link 900 MW/Maritime Link 239 MW Temporary Bipole Fault on the Island Link/150MVAr SC at Soldiers Pond



These results clearly demonstrate that the synchronous condensers at Soldiers Pond, Holyrood and Hardwoods quickly lose synchronism with the rest of the Island machines. As a result, the system voltages oscillate wildly and the dc link repeatedly by-passes or blocks.

To improve this performance, the rating of the synchronous condenser at Soldiers Pond was increased to 300 MVAr. The results are shown in Figure 3-2. The improvement in performance is significant in that all machines retain their synchronism and the system voltages recover quickly and in a stable and damped manner following the temporary fault. The contribution of the high-inertia synchronous condenser at Soldiers Pond amounted to 400 MW at the instant of the fault, when the Island Link is blocked. This contribution decays to zero over 15-cycles and then reverses as the system replaces the power extracted from the inertia of this machine. The reactive contribution of the high-inertia synchronous condenser is also significant, starting from a steady-state output of 250 MVAr and peaking at over 350 MVAr following the restart of the Island Link. The two Holyrood units, operating as synchronous condensers, contributed 110 MW of active support and 110 MVAr of reactive support over the same period.

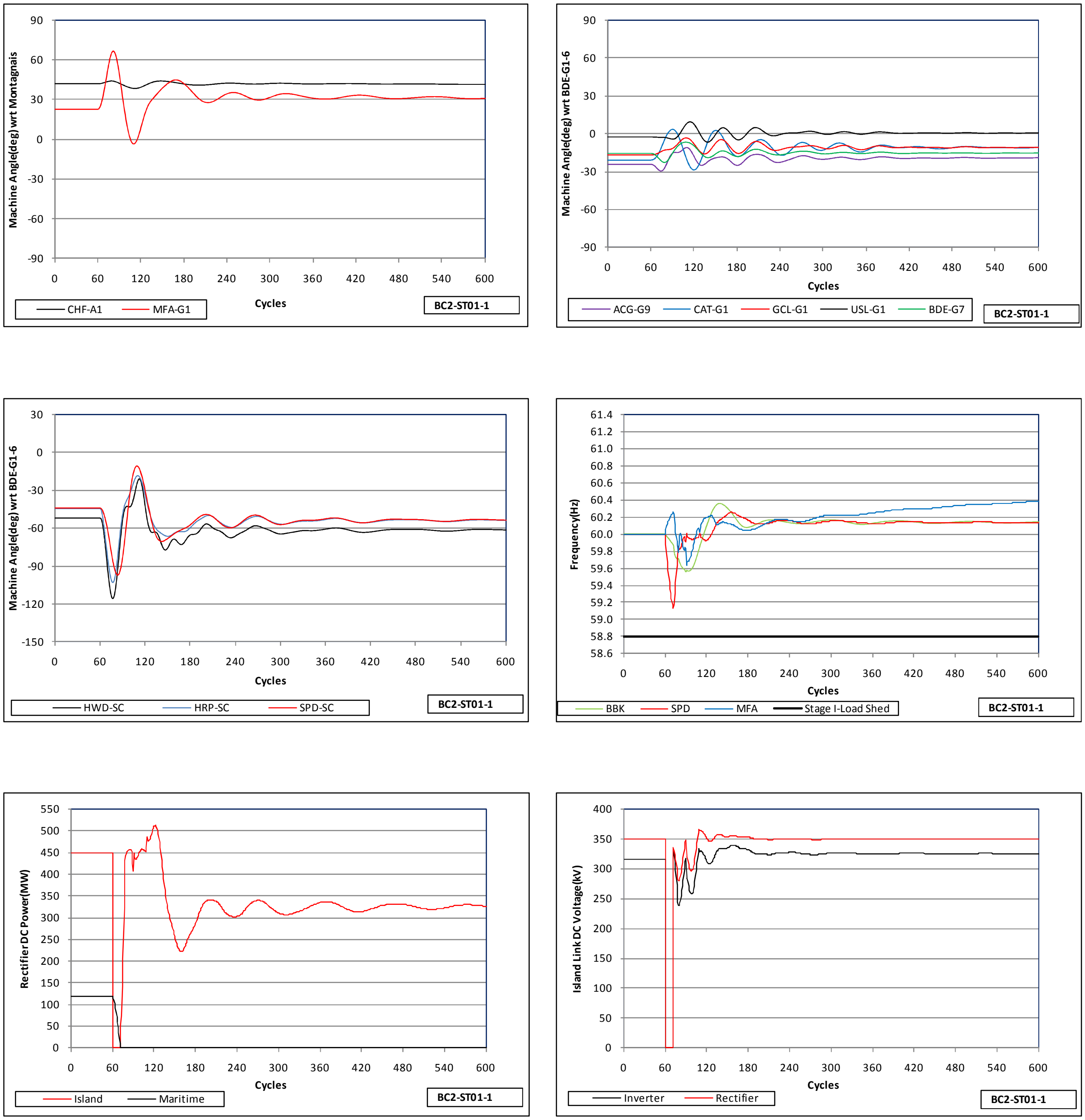
The ramping down of the export over the Maritime Link to zero by the frequency controller at Bottom Brook is critical to the satisfactory recovery of the system. The export power level reduced from 239 MW to zero in approximately 200 ms/ 12-cycles after fault inception.

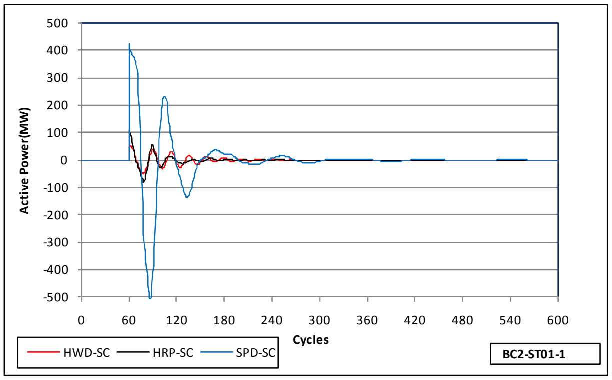
The frequency at Soldiers Pond fell quickly to a value of 59.14 Hz in 200 ms/ 12-cycles and then recovered quickly to 59.8 Hz in the next 100 ms/ 6-cycles. An overshoot of frequency to 60.25 Hz occurred between 1 and 2 s after fault initiation due to the action of the frequency controller on the Soldiers Pond converter. Following this the frequency settled down to a steady-state value of 60.15 Hz. This is well above the 1st-stage load shedding setting of 58.8 Hz, currently used on the system. The frequency at Muskrat Falls is essentially the frequency of the Hydro-Quebec system since Muskrat Falls is synchronously tied to this network via Churchill Falls. The equivalent model of the Hydro-Quebec system used the GENCLS model of PSS®E and as such it cannot be fitted with a governor control model. The governors applied at Muskrat Falls and Churchill Falls are very slowacting and cannot bring the frequency down quickly enough. In practice, the post-fault frequency at Muskrat Falls will be controlled by the overall frequency control scheme of Hydro-Quebec. Since this is not modeled in these simulations, the post-fault frequency at Muskrat Falls is not accurately determined. At some stage, it will be necessary for the frequency control of the Hydro Quebec system to be modeled correctly for such cases to confirm that the frequency at Churchill Falls and Muskrat Falls can be returned to a nominal value within a reasonable time frame.

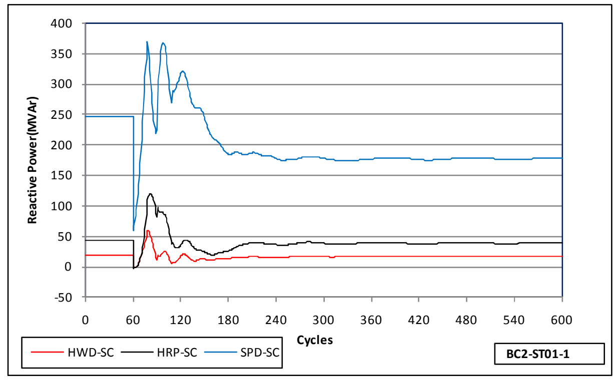
Immediately following the interruption of the bipole, the 315 kV voltage at Muskrat Falls increased to 119% and then decreased back to 100% over the next 267 ms/ 16-cycles. This temporary over-voltage is not considered particularly severe.

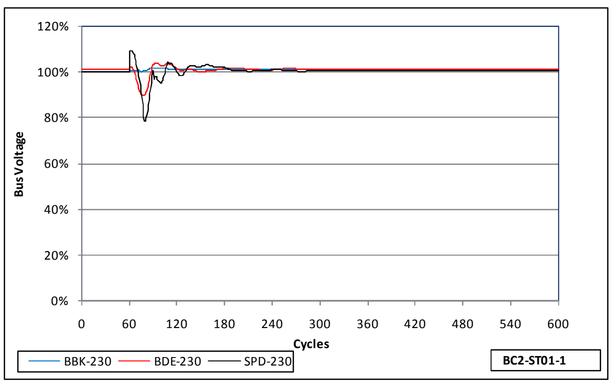
However, even with the reactive support provided by the high-inertia synchronous condensers at Soldiers Pond and the synchronous condensers at Holyrood and Hardwoods, the Soldiers Pond 230 kV ac bus voltage fell momentarily to 80% after fault clearance. At this level there is a significant risk of commutation failure of the inverter.

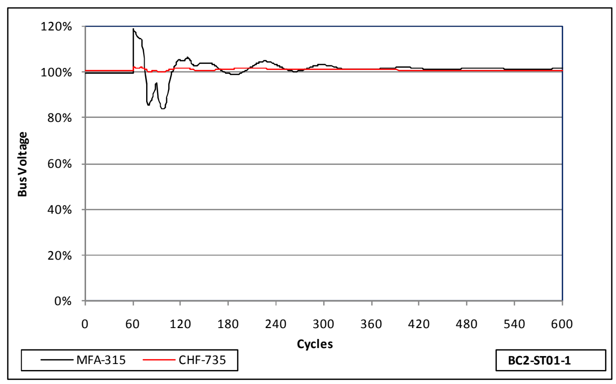
Figure 3-2: BC2-ST01-1, Winter Peak/Island Link 900 MW/Maritime Link 239 MW Temporary Bipole Fault on the Island Link/300MVAr SC at Soldiers Pond




Active Power(MW)
500
400
300
200
100
0
-100
-200
-300
-400
-500
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST01-1


Reactive Power(MVAr)
400
350
300
250
200
150
100
50
0
-50
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST01-1


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST01-1

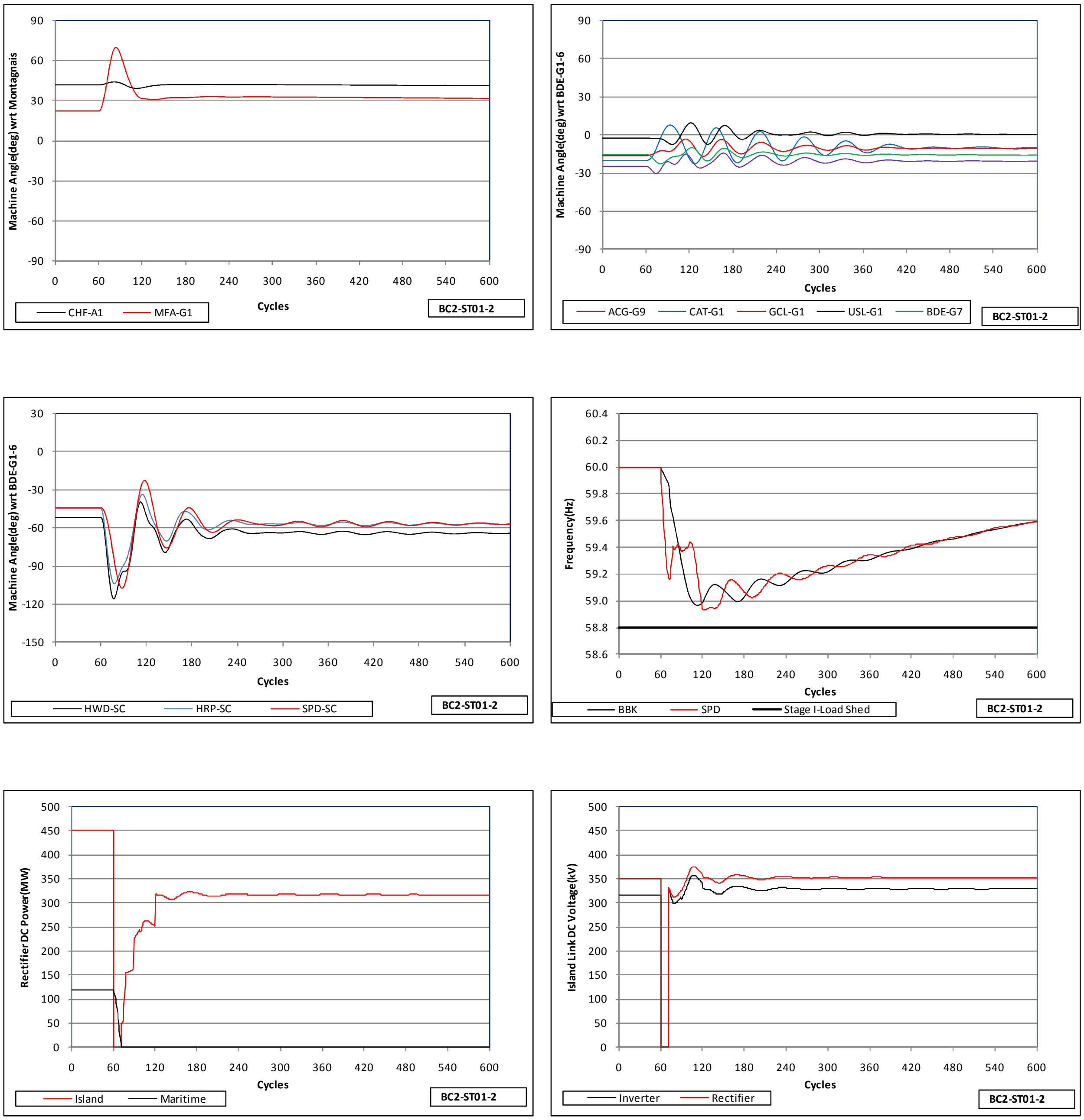

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
MFA-315
CHF-735
BC2-ST01-1

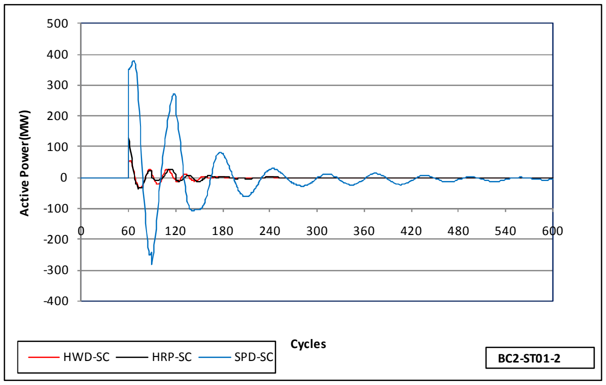
In order to alleviate this problem, the re-start of the Island Link was modified so that the dc power was ramped up in three stages:

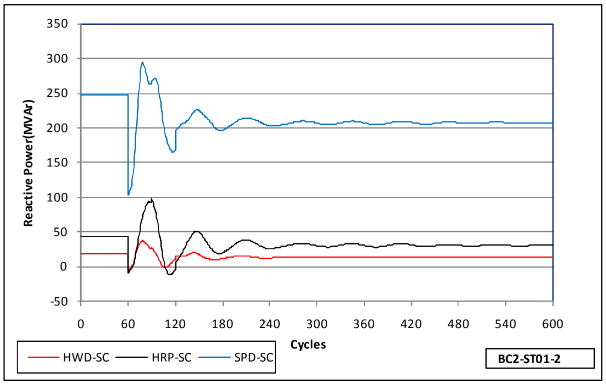
- At 12-cycles/200 ms after fault inception, the dc power was ramped up to 175 MW per pole,
- 18-cycles/300 ms later (30-cycles/500 ms after fault inception), the dc power was ramped up to 260 MW per pole,
- 18-cycles/300 ms later (48-cycles/800 ms after fault inception), the dc power was ramped up to 320 MW per pole,

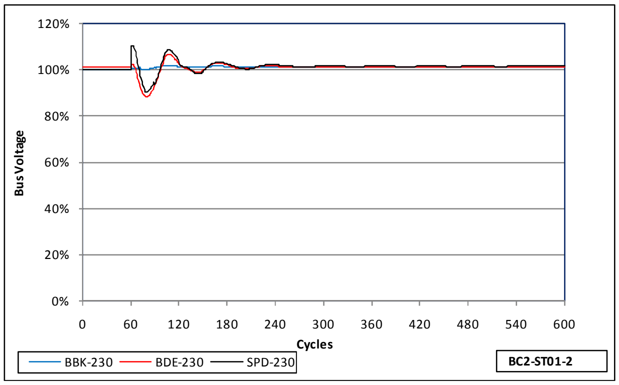
The resulting performance is shown in Figure 3-3. It can be seen that delaying the recovery of the dc power as described above, allows the voltage at Soldiers Pond 230 kV to recover without falling below 90%, thus minimizing the risk of a commutation failure. The staged recovery of the dc power described above is a close approximation to a frequently-used method of controlling the re-start of a dc converter that modifies the dc power level to maintain the ac voltage at or above a pre-set level that will minimize the risk of commutation failure.

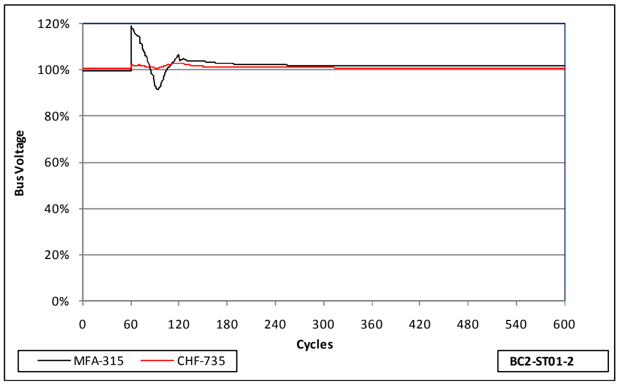
Figure 3-3: BC2-ST01-2, Winter Peak/Island Link 900 MW/Maritime Link 239 MW Temporary Bipole Fault on the Island Link/300MVAr SC at Soldiers Pond Island Link re-started in 3 Stages




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST01-2


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST01-2


Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST01-2


Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST01-2

3.1.2 BC2-ST02: Permanent Pole Fault on the Island Link

The next case considered a permanent dc fault on one pole of the Island Link. Based on the results of the previous case, the high-inertia synchronous condenser at Soldiers Pond was maintained as a 300 MVAr unit.

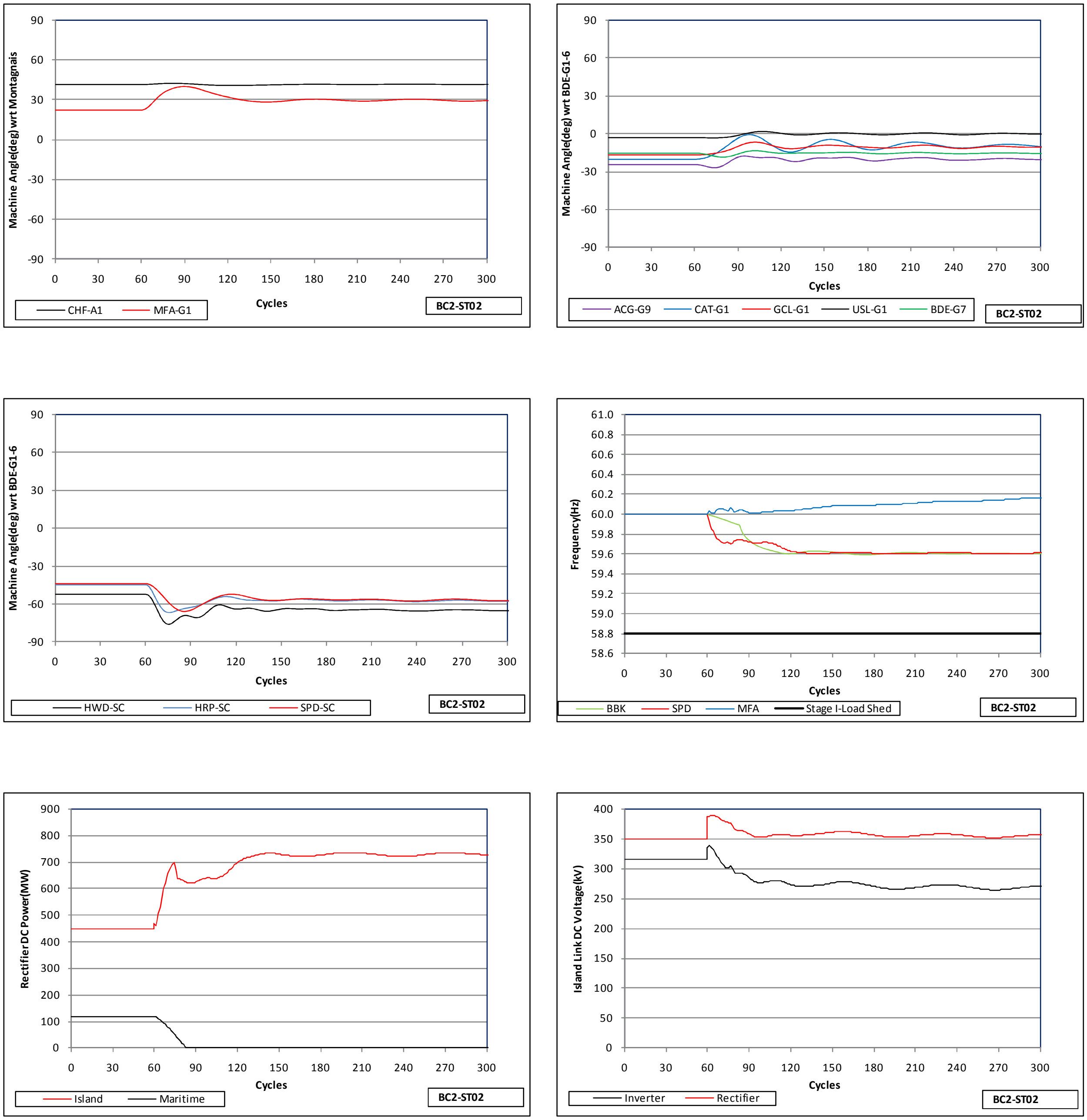
Following the fault, the dc resistance of the healthy pole was increased from 26 Ω to 42 Ω to represent the electrode lines as a return path. The overload capability of each pole can reach 200% in order to compensate for the dc transfer deficit caused by the loss of one pole.

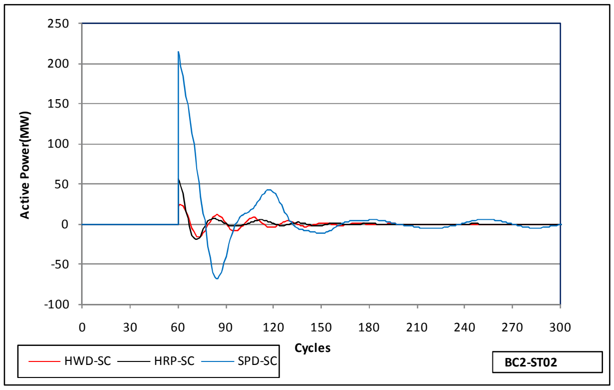
The results are shown in Figure 3-4, and indicate that the system recovers quickly from this disturbance. The frequency controller at Soldiers Pond should remain enabled to ensure a quick response from the healthy pole to compensate for the permanent pole outage. The healthy pole increased its dc power level from 450 MW before the fault to 730 MW after fault clearance.

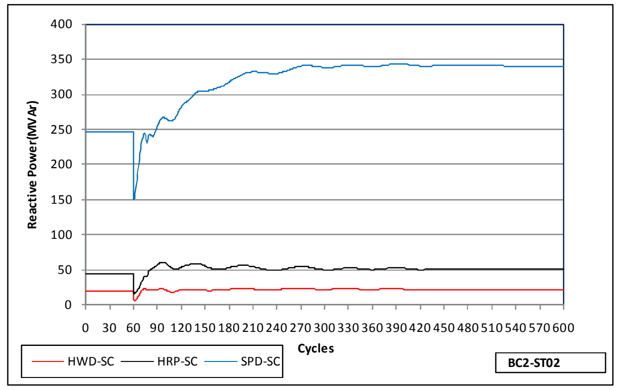
It was observed that the high-inertia synchronous condenser at Soldiers Pond settled down after the disturbance with an output of 340 MVAr, which is above its rated value of 300 MVAr. This situation will be temporary until such time as the converter transformer on the healthy pole makes adjustments to bring the firing angle (γ) back to its nominal value of 18 degrees. This will reduce the reactive power requirement of the converter and lower the loading on the synchronous condenser to below its rated value.

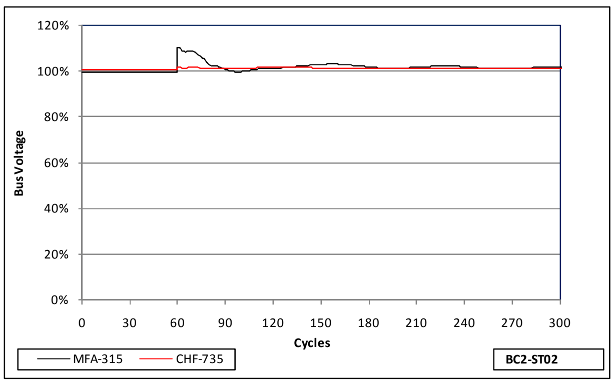
The frequency at Soldiers Pond stabilized at a value of 59.6 Hz. This value represents the balance point at which the frequency controller at Soldiers Pond provides a steady ordered value of dc power to the converter since the frequency is not changing. A slower-acting frequency controller will also be required to correct the frequency slowly back to 60 Hz if sufficient additional capacity is available on the Island Link to do this. This type of action can wait until the system has settled down after the disturbance and could even be handled manually by adjusting the power order on the Island Link or adjusting the available Island generation levels.

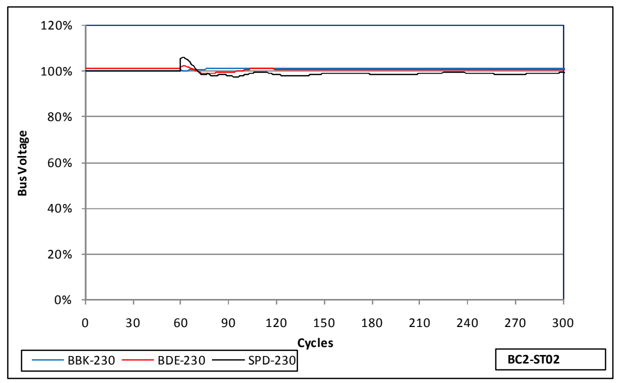
Figure 3-4: BC2-ST02, Winter Peak/Island Link 900 MW/Maritime Link 239 MW Permanent Pole Outage on the Island Link/300MVAr SC at Soldiers Pond

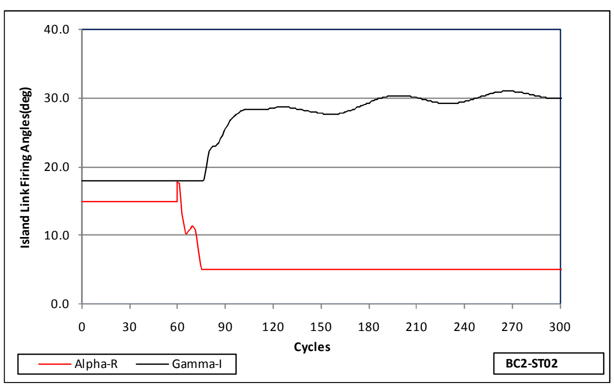



Active Power(MW)
250
200
150
100
50
0
-50
-100
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC HRP-SC SPD-SC
BC2-ST02


Reactive Power(MVAr)
400
350
300
250
200
150
100
50
0
0 30 60 90 120 150 180 210 240 270 300 330 360 390 420 450 480 510 540 570 600
Cycles
HWD-SC HRP-SC SPD-SC
BC2-ST02


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
MFA-315 CHF-735
BC2-ST02


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
BBK-230 BDE-230 SPD-230
BC2-ST02


Island Link Firing Angles(deg)
40.0
30.0
20.0
10.0
0.0
0 30 60 90 120 150 180 210 240 270 300
Cycles
Alpha-R Gamma-I
BC2-ST02

3.1.3 BC2-ST03: Three Phase Fault at Muskrat Falls 315 kV on line to Churchill Falls

A 100 ms/ 6-cycle, 3-phase fault was applied at Muskrat Falls 315 kV resulting in the outage of one 315 kV circuit between Churchill Falls and Muskrat Falls. The voltage depression at the Muskrat Falls converter station will result in blocking of the converters at Muskrat Falls and an interruption of the export over the Island Link, in much the same way as the temporary bipole fault discussed earlier. However, in this case, because there are only 3 units operating at Muskrat Falls, the balance of the 900 MW pre-fault export and the load at Happy Valley is supplied from Churchill Falls. After fault clearance, restoration of the export level means that all the balance of power from Churchill Falls now has to flow down a single circuit from Churchill Falls. This is to some extent offset by the fact that the export over the Maritime Link will have been reduced to zero. However, when the Island Link first comes back into service after the block, the frequency controller at Soldiers Pond will not be operational since it was delayed for 500 ms in BC2-ST01-1. This delay represented the minimum time to allow for satisfactory recovery of the ac system. Deactivating the frequency controller helps the recovery of the ac system during faults at nearby buses. This means that the Island Link will return to its previous export level of 900 MW. The results are shown in Figure 3-5.

It can be seen that the system appears to perform reasonably through the duration of the fault and that recovery is being achieved when at the instant that the frequency controller at Soldiers Pond is enabled (1.50 s in the plots below) the frequency at Soldiers Pond is marginally below 60 Hz and the controller signals an increase in the dc power. This increase is sufficient to result in a depression of the dc and ac voltages to the point where the converters block momentarily, re-start and then block again. To avoid this situation which could, in practice lead to multiple commutation failures, the response of the frequency controller was modified such that:

- 500 ms after the initiation of the fault, the power order on the Island Link was reduced from 450 MW per pole to 320 MW per pole. This value is based on the fact that the Maritime Link has been shut down and the Island Link can be reduced by approximately 240-250 MW to accommodate this.

- The frequency controller was disabled until such time as the frequency at Soldiers Pond returned to 60 Hz.

The results are shown in Figure 3-6 where it can be seen that the system recovers satisfactorily with the reduction in the dc power order allowing the ac and dc voltages to recover to satisfactory levels where a block will not occur. The frequency controller actually came into operation approximately 4 s/ 240-cycles after fault initiation. During the fault period, the frequency at Soldiers Pond fell to 59.4 HZ and during the recovery period, before the frequency controller is re-activated, the frequency varied with a minimum value of 59.8 Hz. Under the action of the frequency controller, the dc power was slightly reduced from 320 MW per pole to 315 MW per pole to maintain the frequency at 60 Hz.

This type of control will require an auxiliary input signal to inform the converter control that the 315 kV line from Churchill Falls to Muskrat Falls has been tripped. This will be used to trigger the reduction in power order. Since the line is tripped at 100 ms/ 6-cycles and the power order reduction does not occur until 500 ms/ 30-cycles after fault initiation, there is ample time to acquire and process this information.

Figure 3-5: BC2-ST03, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Muskrat Falls 315 kV on line to Churchill Falls

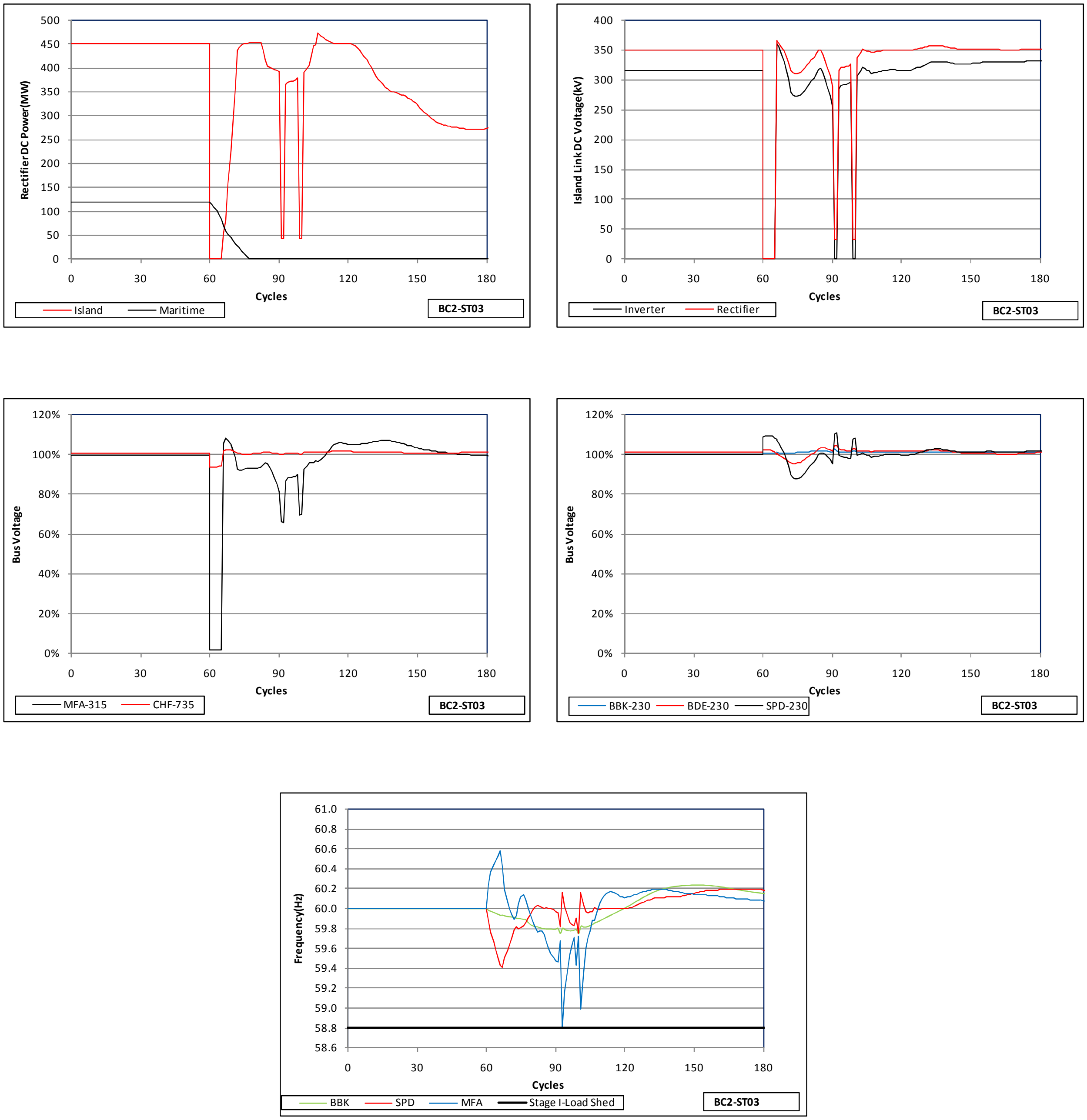
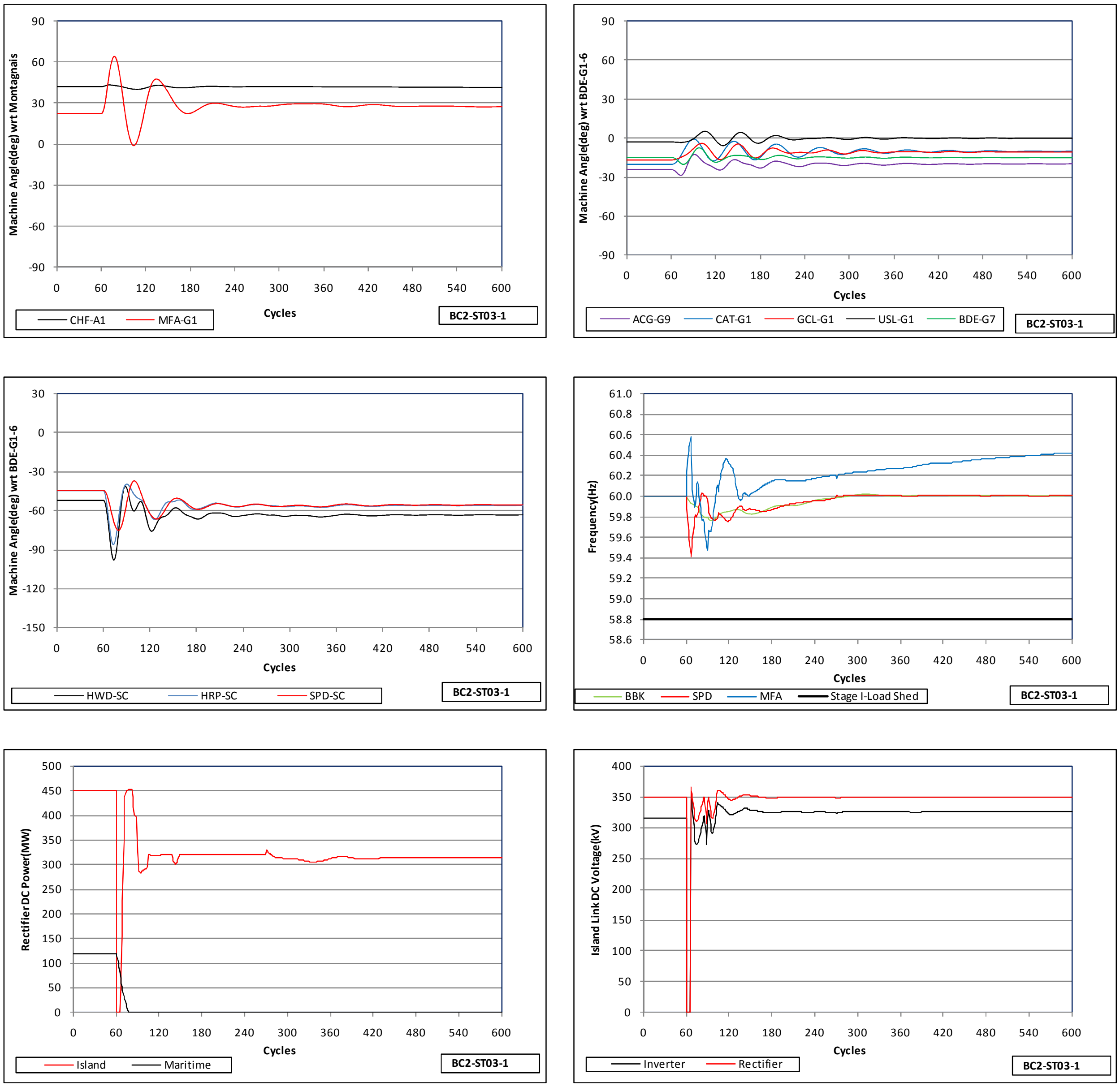
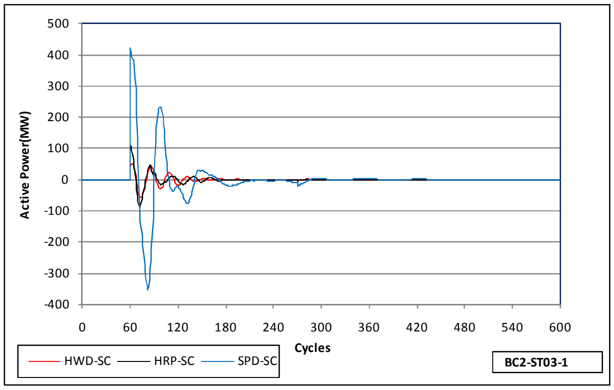
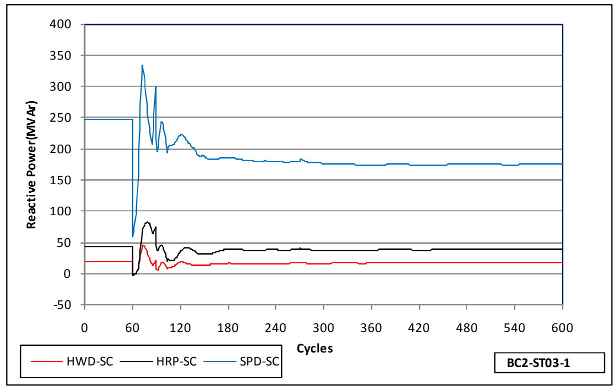


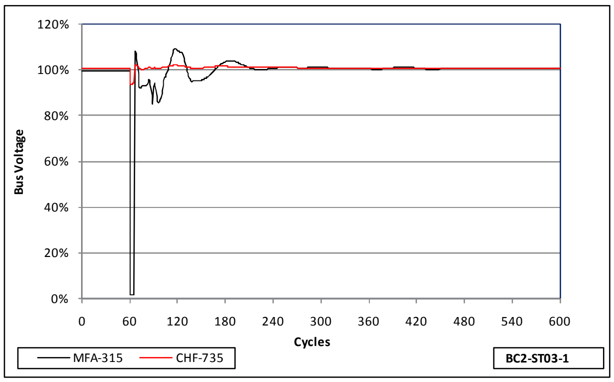
Figure 3-6: BC2-ST03-1, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Muskrat Falls 315 kV on line to Churchill Falls (Power Order Reduction+Frequency Controller Delayed Operation)

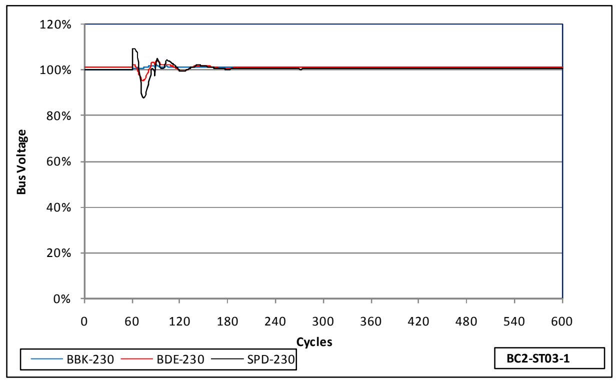


SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	29









3.1.4 BC2-ST04: Three Phase Fault at Bay d'Espoir 230 kV on line to Western Avalon

In this case a 6-cycle, 3-phase fault was applied at Bay d'Espoir 230 kV with a post-fault outage of the 230 kV line to Western Avalon.

The results are shown in Figure 3-7.

Since the voltage at Bay d'Espoir falls to zero during the fault, the voltages at Bottom Brook and Soldiers Pond suffer major depressions (below 80%). This will cause the Bottom Brook and Soldiers Pond converters to block immediately, reducing the power on the Island and Maritime Links to zero. However, as in previous cases, the Maritime Link was then held at zero power for the duration of the simulation. It may be noticed that the Island Link rectifier power does not reduce to zero in this case. This is a result of the type of model used in the program. The inverter model cannot model a commutation failure, such as would occur when the ac system voltage is depressed due to an ac fault. To get around this problem the inverter model has a feature that automatically bypasses (short-circuits) the inverter on the dc side. When this occurs, the rectifier increases its firing angle to reduce the dc current to its minimum value. This accounts for the small amount of power seen at the rectifier end due to the minimum dc current circulating around the two poles. This current does not pass through the inverter.

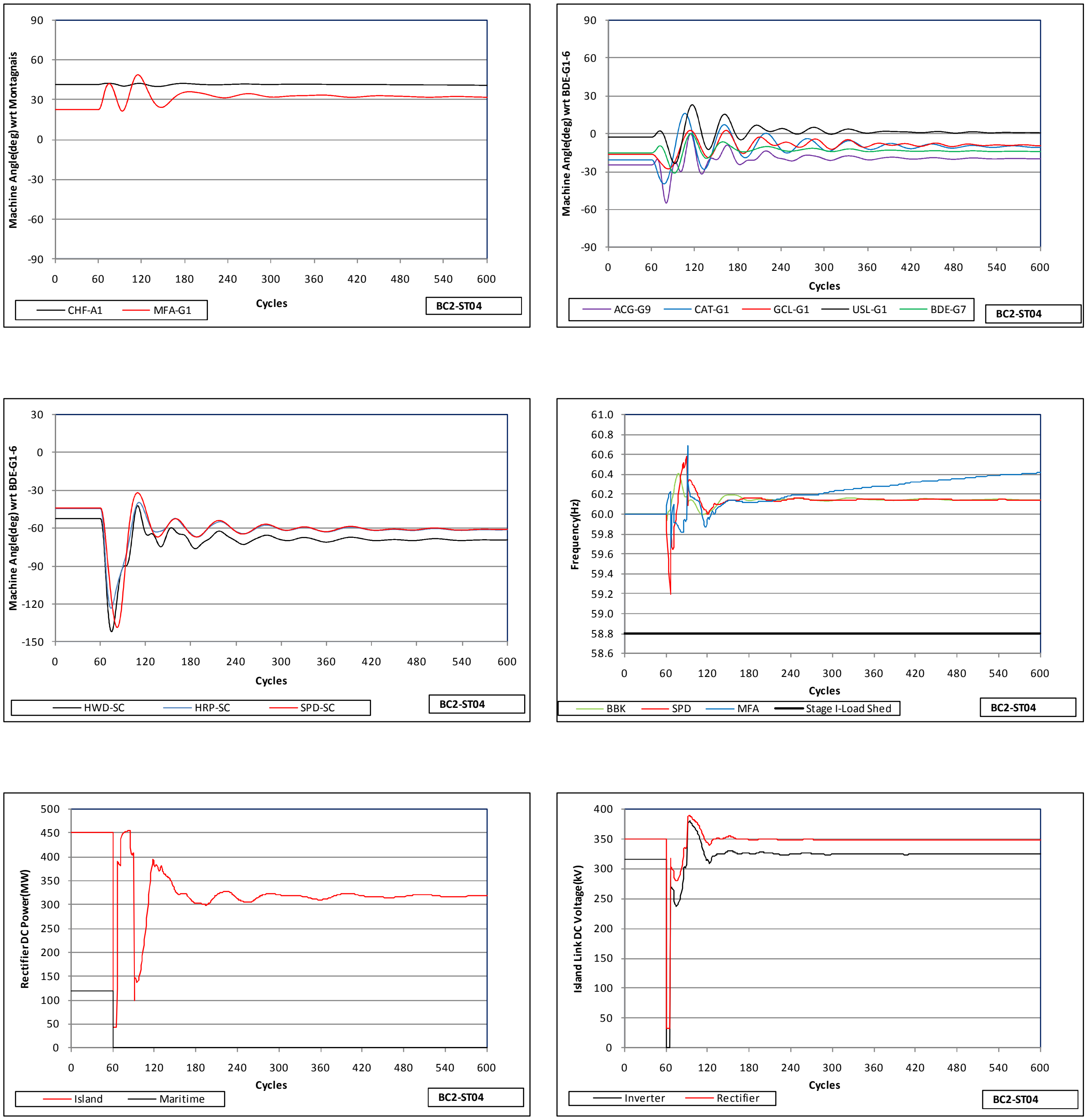
The system remained in synchronism and recovered quickly from the fault with 300 MVAr of synchronous condensers operating at Soldiers Pond. The power on the Island Link was reduced from 900 MW to approximately 640 MW as a result of the removal of the Maritime Link export. The frequency at Soldiers Pond fell momentarily to 59.2 Hz and following the re-start of the Island Link rose for a short period to 60.6 Hz at which time the frequency controller at Soldiers Pond was re-activated (500 ms following the fault) and stabilized the frequency between 60.1-60.2 Hz by reducing the Island Link dc power.

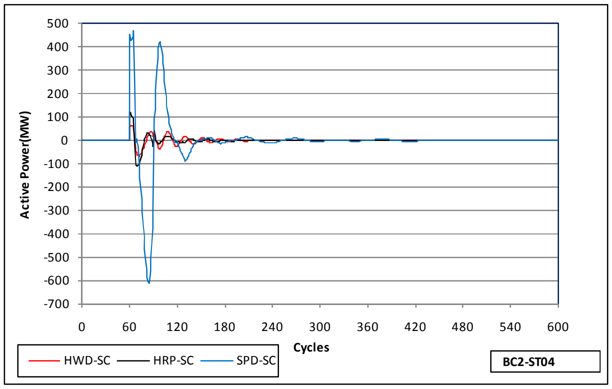
The high-inertia synchronous condenser at Soldiers Pond contributed up to 450 MW and 450 MVAr to the system during and after fault clearance.

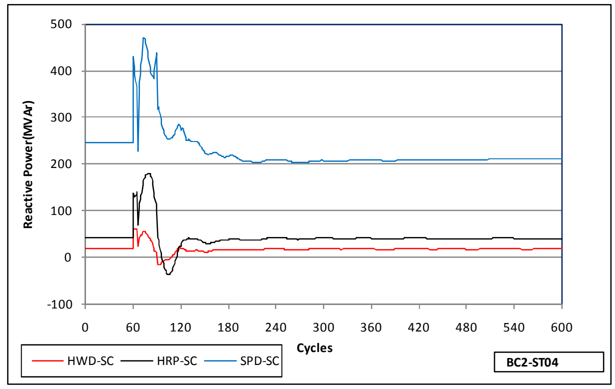
The rapid frequency decline at Soldiers Pond (0.8 Hz) occurred over the fault period (6-cycles/100 ms). This corresponds to a rate of change of frequency of 8 Hz/s, higher than the normal rate of change on the system, which is closer to 3 Hz/s. The reason for this higher rate of change of frequency is attributed to the fact that the three-phase fault at Bay d'Espoir effectively isolates Soldiers Pond from the inertia of the Bay d'Espoir generators and all other generators to the west of Bay d'Espoir during the fault period. The total inertia of the system (9,000 MW-s) is therefore not available to support the frequency at Soldiers Pond during this time. The only inertia available to Soldiers Pond comes from the synchronous condensers at Soldiers Pond itself, Holyrood and Hardwoods. This amounts to approximately 2,000 MW-s. The total load to the east of Bay d'Espoir is approximately 1,100 MW but, since the voltage is depressed, the effective load is approximately 800 MW. This gives an effective inertia constant in that part of the system of 3.45 MWs/MVA with a run-down time of 6.9 s. This translates to a rate of change of frequency of 8.7 Hz/s which is close to the value found in the simulation.

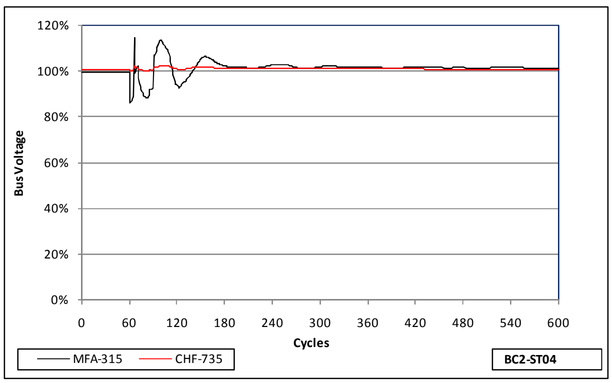
However, it can again be noted that following fault clearance and re-establishment of the Island Link, the voltage at Soldiers Pond 230 kV fell momentarily to less than 90%, raising the possibility of commutation failure on the Island Link inverter. It was observed that the voltage at Soldiers Pond 230 kV returned to barely above 90% following fault clearance and decreased from that value to 80% as the dc power was re-started. The main cause of this poor post-fault voltage appears to be even lower post-fault voltages at Western Avalon and Bay d'Espoir.

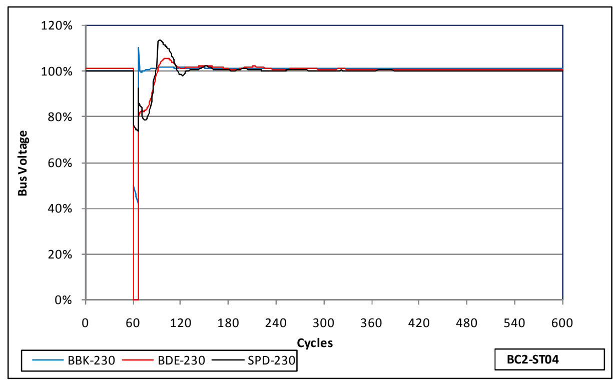
Figure 3-7: BC2-ST04, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV on line to Western Avalon




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST04


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST04


Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST04


Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST04

Various strategies were investigated to alleviate this under-voltage:

- staging of the dc re-start,
- replacement of the exciters at Bay d'Espoir with high-gain, high ceiling exciters,
- the application of 50% series compensation to the 230 kV lines from Bay d'Espoir to Sunnyside [TL202 &TL206] and from Bay d'Espoir to Western Avalon [new line],
- the application of an SVC at Western Avalon,
- the application of an SVC at Bay d'Espoir, and
- increasing the number of synchronous condensers at Soldiers Pond and Holyrood.

The only effective solutions were:

- the application of an SVC at Bay d'Espoir or Western Avalon together with the third synchronous condenser at Holyrood, and
- to connect the third synchronous condenser at Holyrood and to increase the synchronous condenser rating at Soldiers Pond to 450 MVAr.

The other strategies failed to correct the voltage dip at Soldiers Pond sufficiently to remove the risk of commutation failure following the fault clearance.

The system performance with the SVC connected at Bay d'Espoir is shown in Figure 3-8 and the performance with the additional synchronous condensers at Holyrood and Soldiers Pond is shown in Figure 3-9.

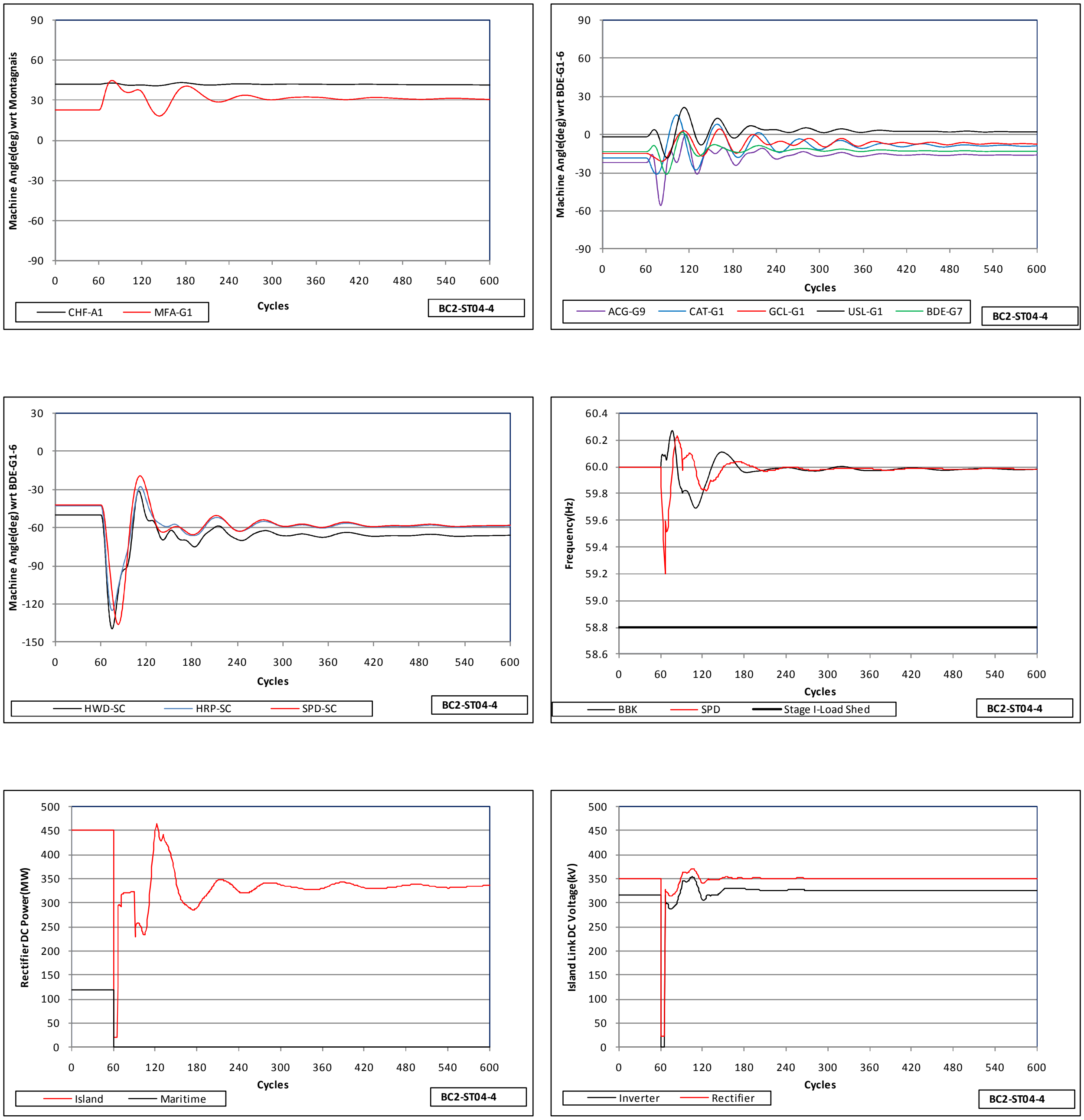
The SVC at Bay d'Espoir produced up to 250 MVAr following the fault clearance. It is worth noting that the rating of ±250 MVAr for this SVC corresponds exactly to the reactive capability of a 500 MW VSC converter, similar to one that could be employed at Bottom Brook for the Maritime Link.

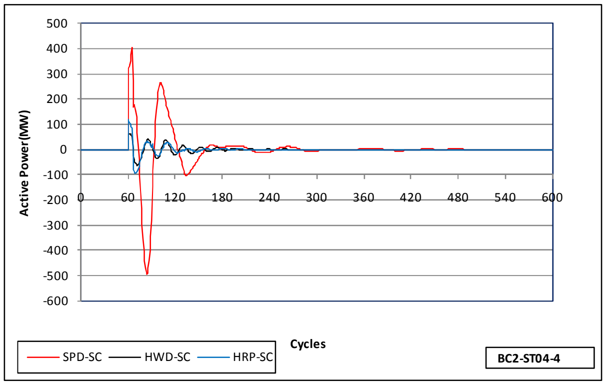
The synchronous condensers at Soldiers Pond produced close to 500 MW and 375 MVAr during and immediately after the fault, maintaining the voltage at Soldiers Pond 230 kV to 90% or above following fault clearance.

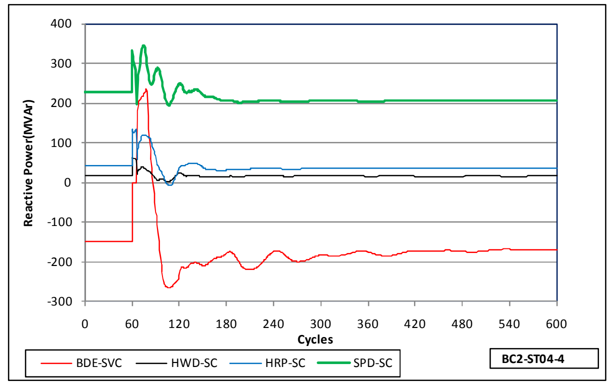
It can be seen that this fault case constitutes the defining case for the synchronous condenser requirements at Soldiers Pond.

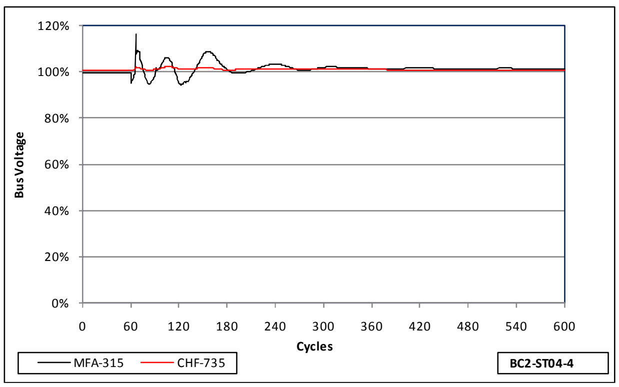
SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	36

Figure 3-8: BC2-ST04-4, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV on line to Western Avalon +/-250MVAR-SVC at Bay d'Espoir+3-SC at Holyrood




Active Power(MW)
Cycles
SPD-SC
HWD-SC
HRP-SC
BC2-ST04-4


Reactive Power(MVAr)
Cycles
BDE-SVC
HWD-SC
HRP-SC
SPD-SC
BC2-ST04-4


Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST04-4

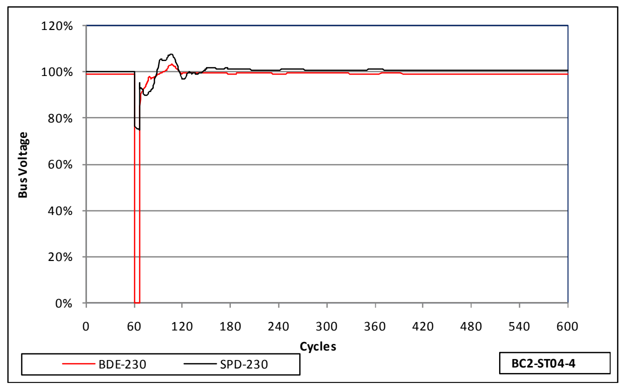
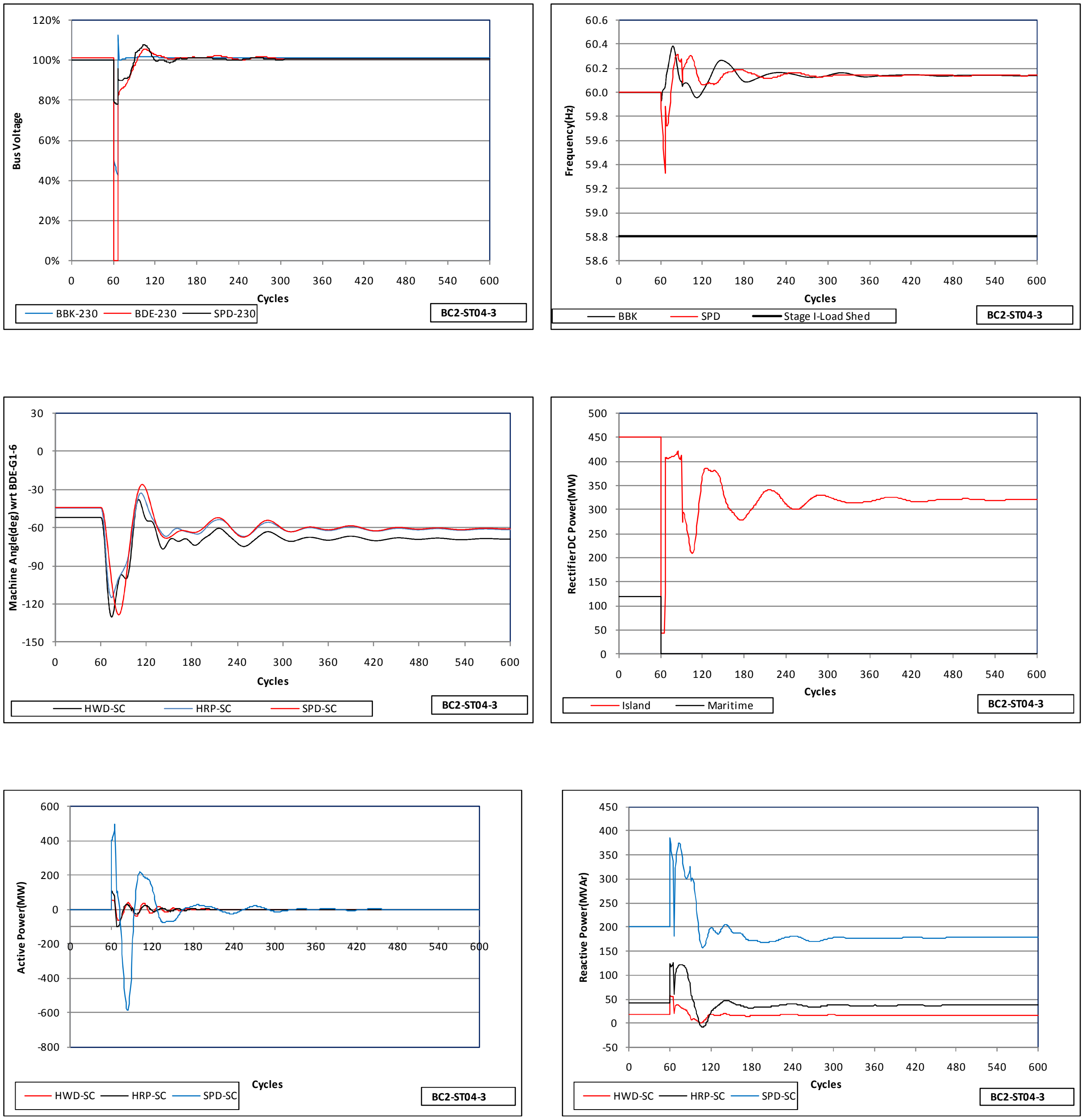

Bus Voltage
Cycles
BDE-230
SPD-230
BC2-ST04-4

Figure 3-9: BC2-ST04-3, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV on line to Western Avalon 450MVAR-SC at Soldiers Pond+3-SC at Holyrood



3.1.5 BC2-ST05: Three Phase Fault at Soldiers Pond 230 kV on line to Western Avalon (TL217W)

In the case of a 6-cycle, 3-phase fault at Soldiers Pond 230 kV on the line to Western Avalon, TL217W (Figure 3-10), the voltage depression at Soldiers Pond was sufficient to cause the Island Link to block. However, the voltage and frequency depressions at Bottom Brook were not severe enough to cause automatic blocking of the Maritime Link.

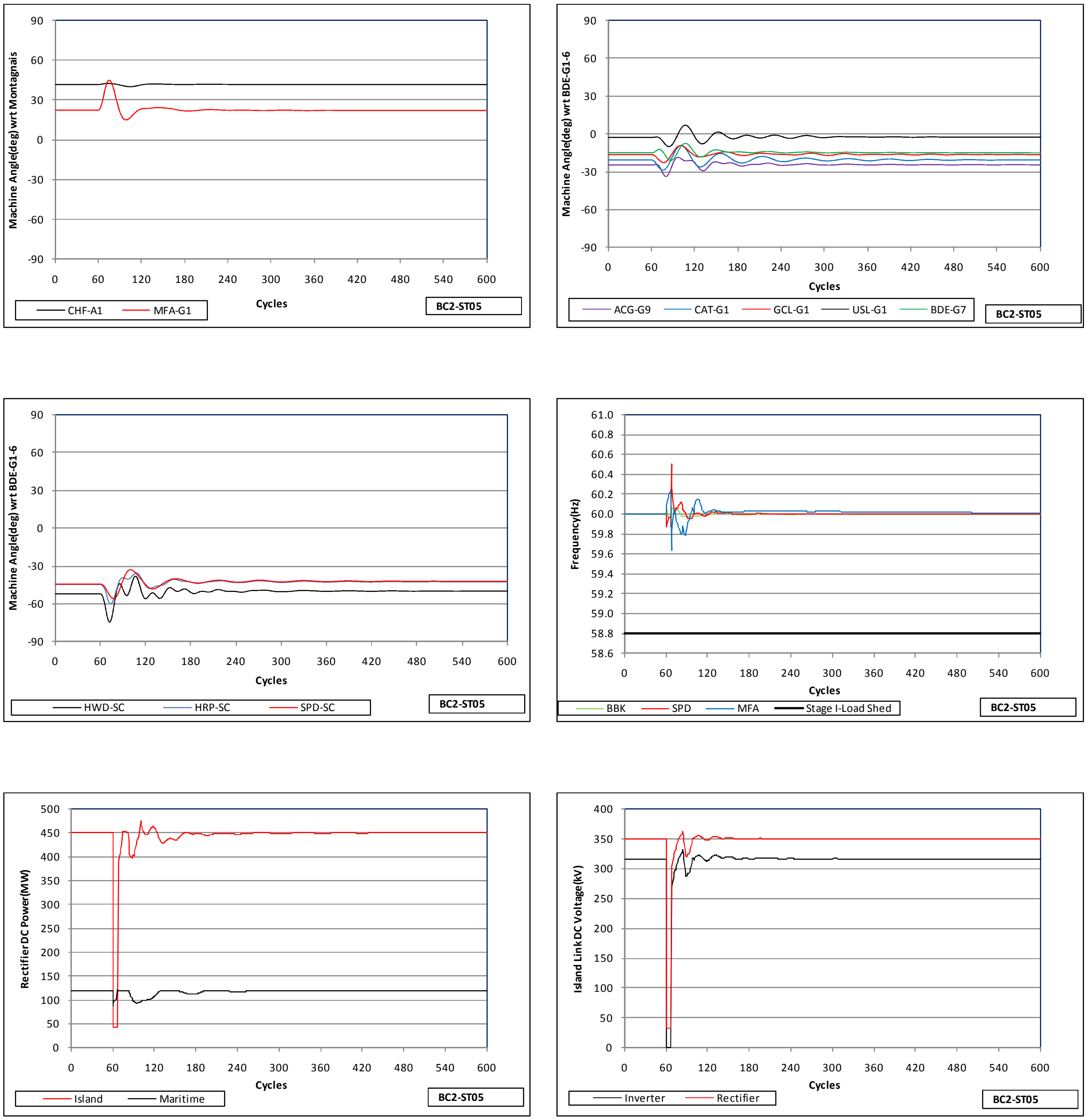
Following fault clearance, both dc links recovered quickly to their pre-fault levels and the system remained in synchronism with the system voltages recovering quickly.

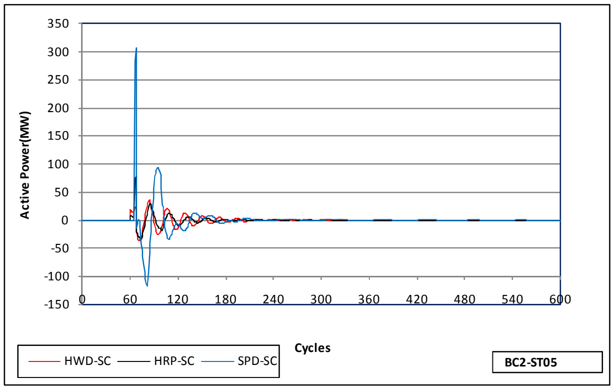
With only 300 MVAr of high-inertia synchronous condensers at Soldiers Pond and two synchronous condensers running at Holyrood, the same problem with the Soldiers Pond 230 kV voltage falling below 90% following fault clearance was seen in this case as in the previous case. To alleviate this problem it was necessary to reduce the export over the Maritime Link to zero and to delay the re-start of the Island Link until the voltage had recovered sufficiently at Soldiers Pond. This again approximates the control function that regulates the timing, level and rate at which the dc is ramped up as a function of the inverter ac bus voltage. The system performance is shown in Figure 3-11.

It was not found necessary to increase the rating of the synchronous condenser at Soldiers Pond.

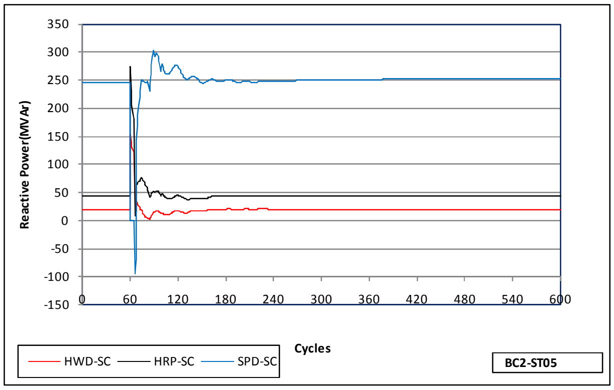
A similar result was found for a 3-phase fault at Sunny Side on the line to Western Avalon [TL203].

Figure 3-10: BC2-ST05, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Soldiers Pond 230 kV on line to Western Avalon (TL217W)

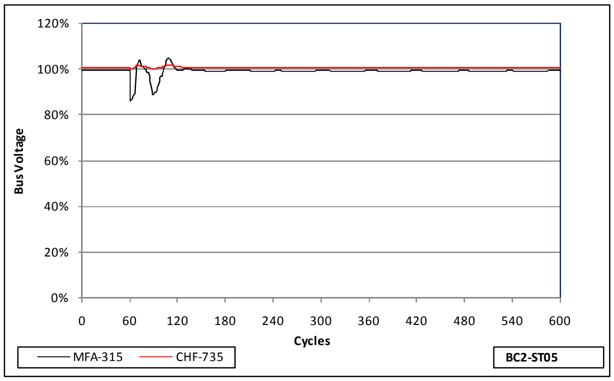




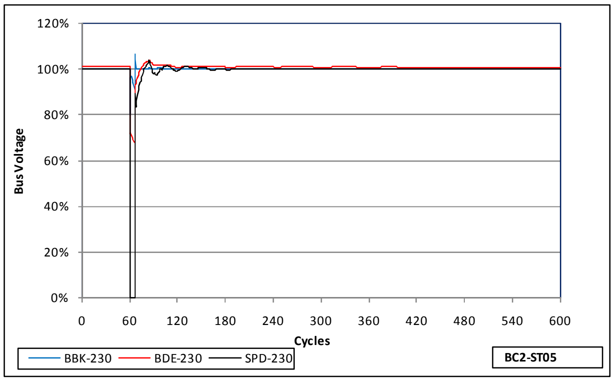
Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST05



Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST05

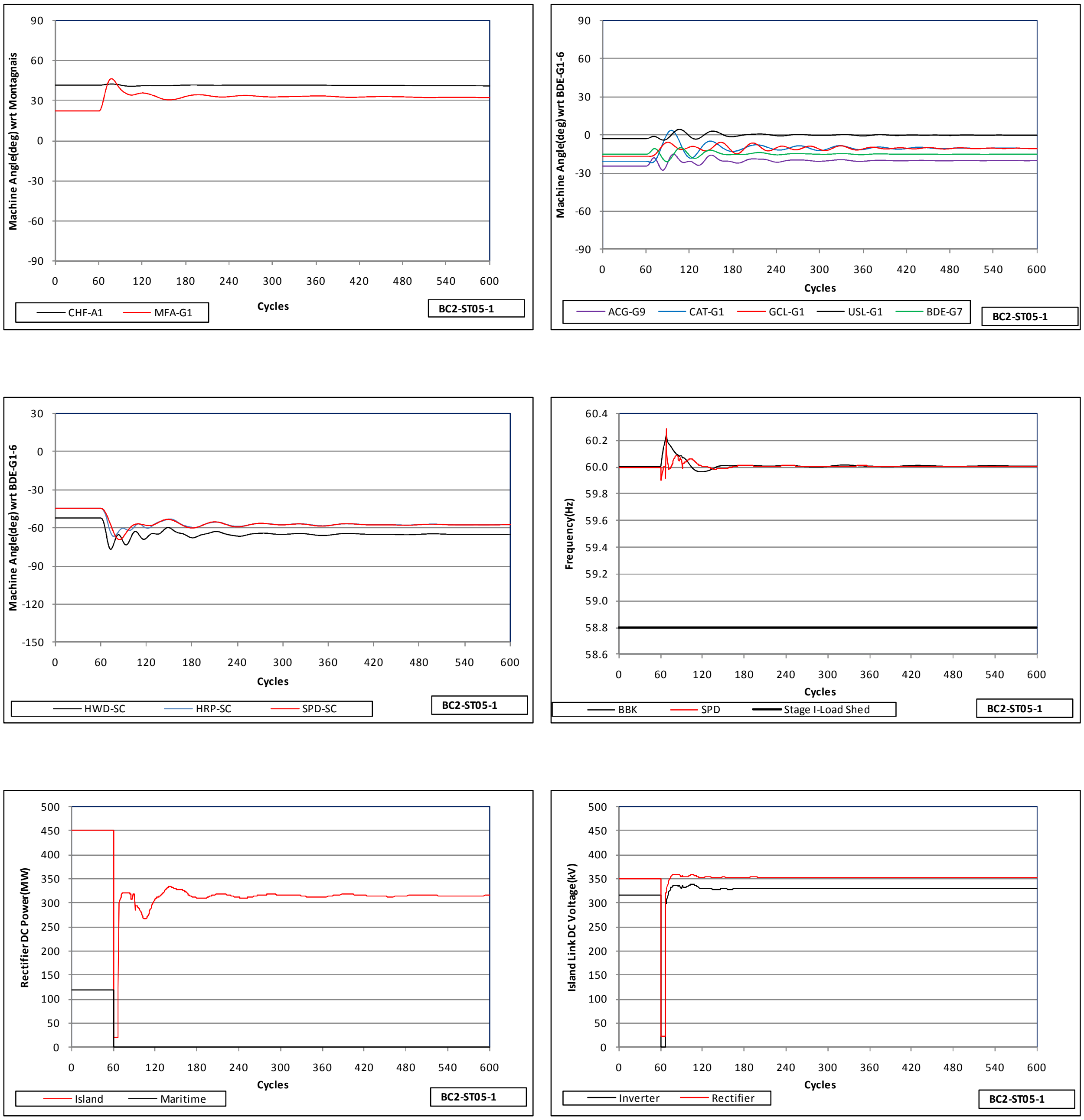


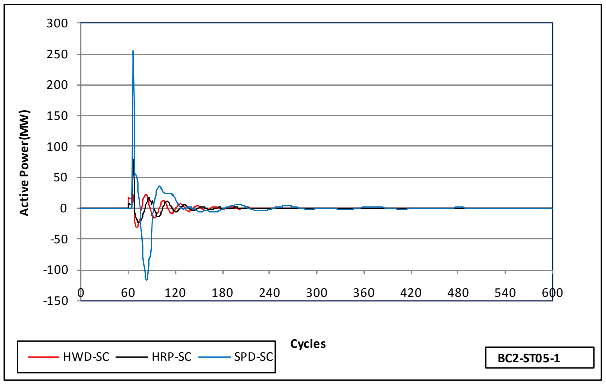
Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST05

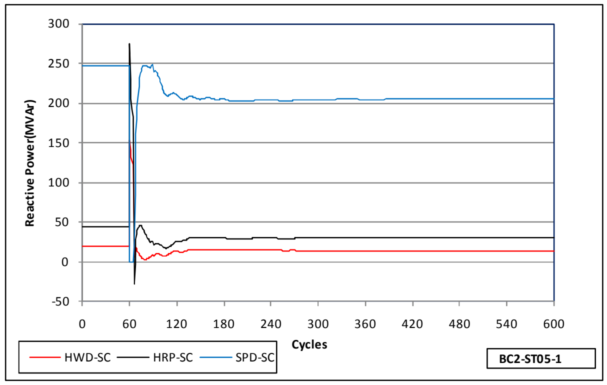


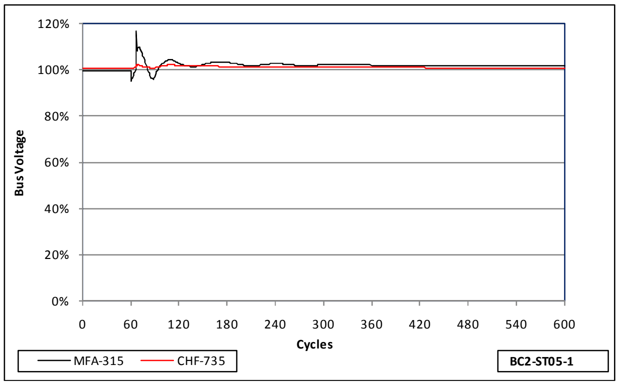
Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST05

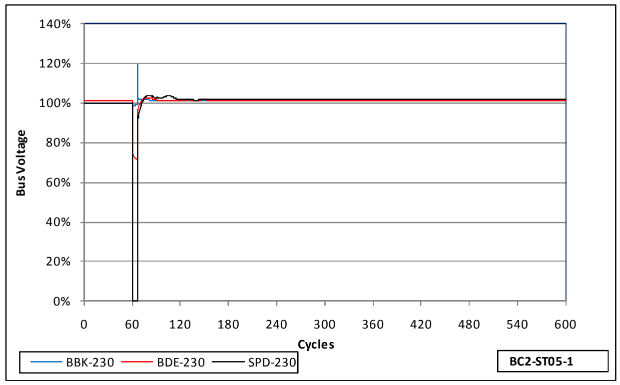
Figure 3-11: BC2-ST05-1, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Soldiers Pond 230 kV on line to Western Avalon (TL217W), Island Link re-start delayed




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST05-1


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST05-1


Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST05-1

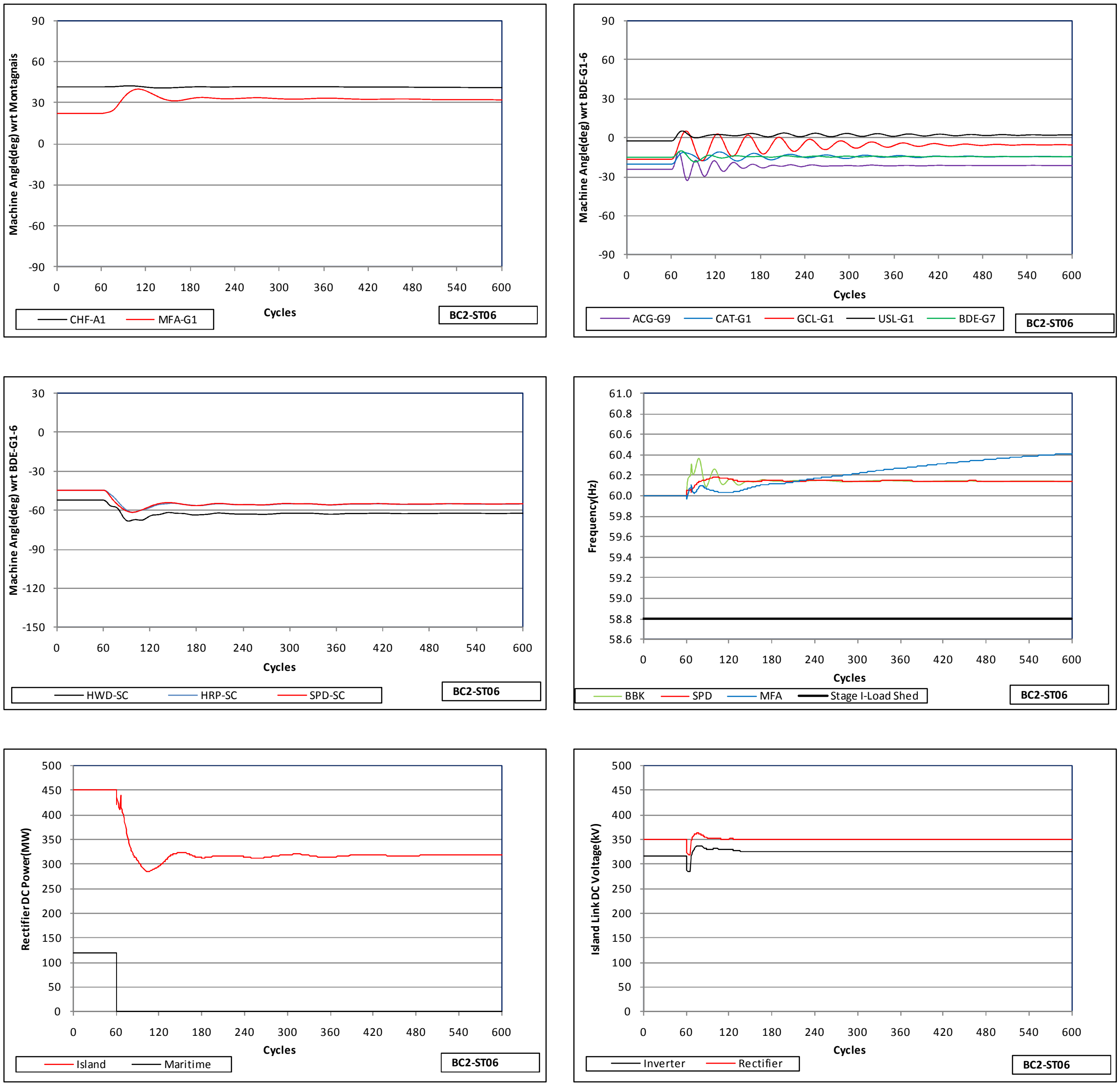

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST05-1

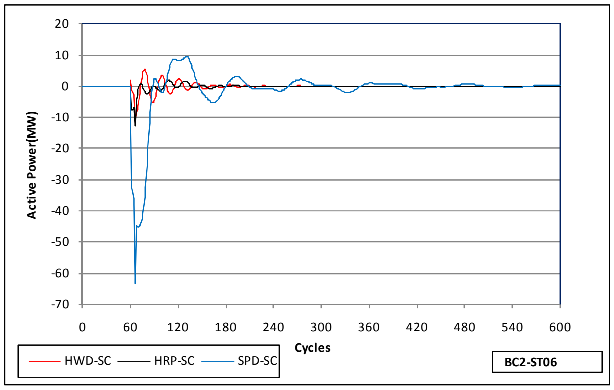
3.1.6 BC2-ST06: Three Phase Fault at Bottom Brook 230 kV on line to Granite Canal

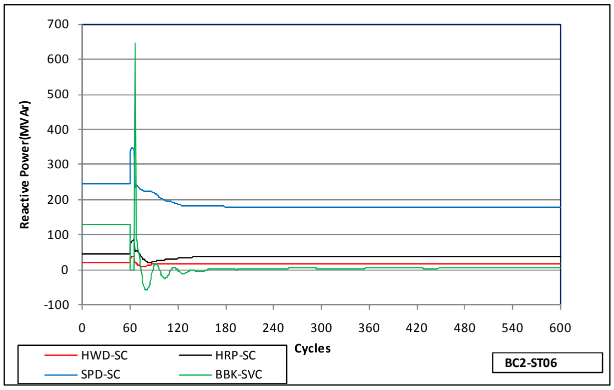
In this case, the voltage at Bottom Brook collapsed to zero, resulting in blocking of the Maritime Link (Figure 3-12). The Island Link continued to operate through the fault and the system recovered quickly. The dc power level on the Island Link was subsequently reduced due to the loss of the Maritime Link and the system frequency stabilized at 60.1-60.2 Hz.

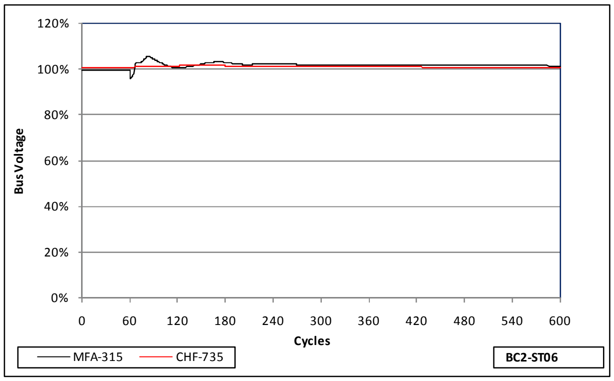
Due to action of the SVC at Bottom Brook in response to the fault, the post-fault voltage at Bottom Brook increased to approximately 130% for a few cycles until the SVC was able to reduce its output. This temporary over-voltage lasted only for a few cycles and is well within the temporary over-voltage capability of zinc oxide arresters (160% of maximum system voltage for 1s) and the substation equipment. The exact duration will depend upon the design of the SVC itself, but clearly, as shown in the plot of the reactive output of the Bottom Brook SVC reactive power, a fast-acting device is required. The steady-state rating of this SVC was determined in the load flow studies report to be +320/-100 MVAr. If VSC technology is employed for the Bottom Brook converter, the inherent reactive control properties of such converters can be usefully employed to avoid the need for an SVC at this location. Typically, VSC converters can provide or absorb reactive power. In Appendix C, two PQ-curves from ABB and Siemens show that the reactive power can reach 30%-40% and 25% of the rated power respectively when the VSC operates at rated power. For a 500 MW converter this would translate to a reactive capability of ±125 MVAr. The balance of 195 MVAr for the reactive production requirements could then be met with a smaller SVC or even shunt capacitors.

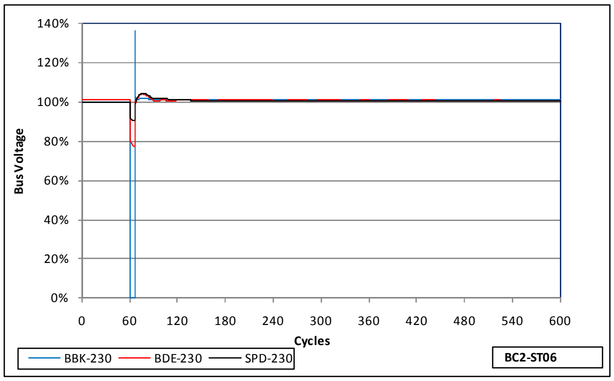
Figure 3-12: BC2-ST06, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Bottom Brook 230 kV on line to Granite Canal




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST06


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BBK-SVC
BC2-ST06

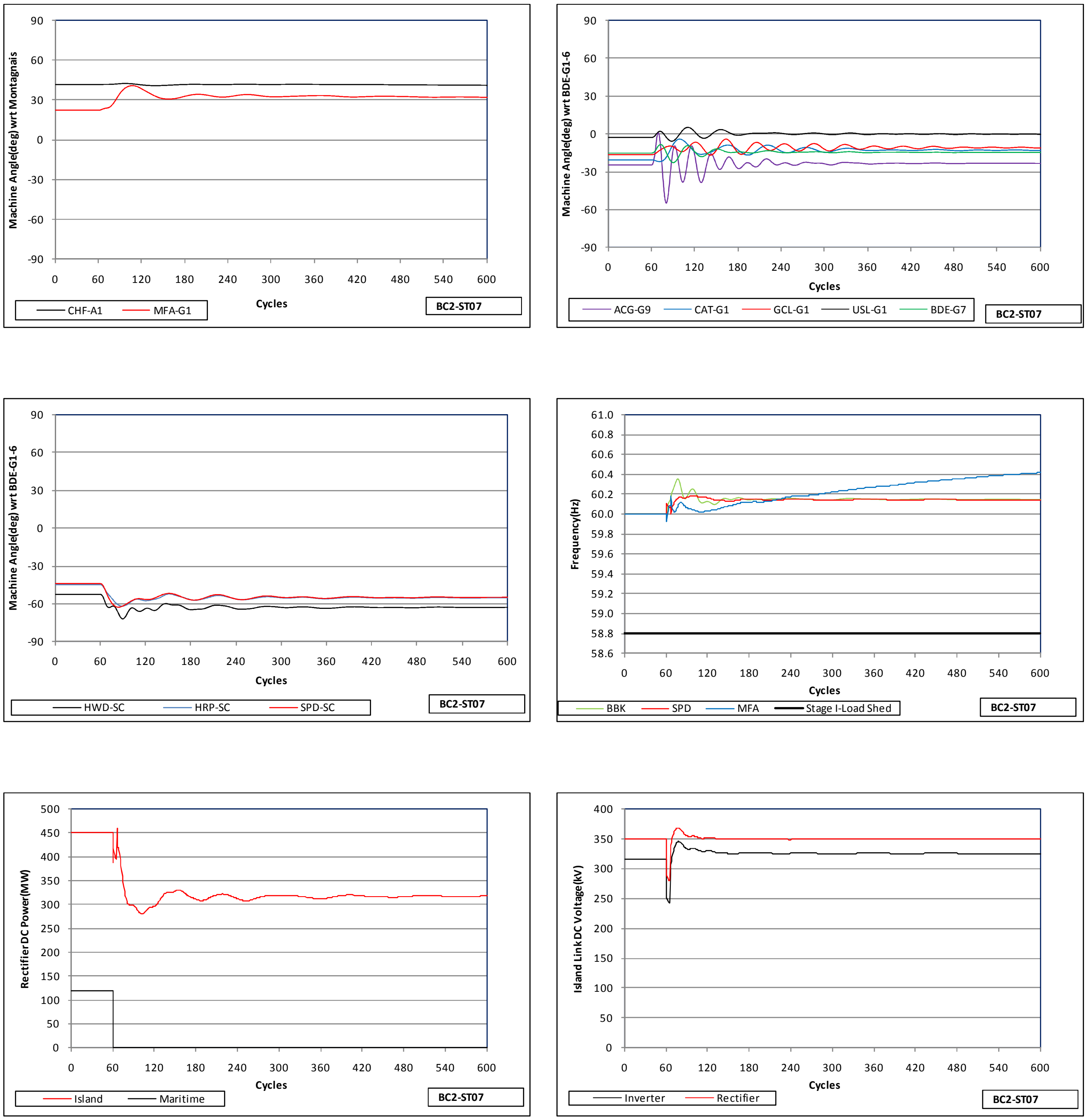

Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST06


Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST06

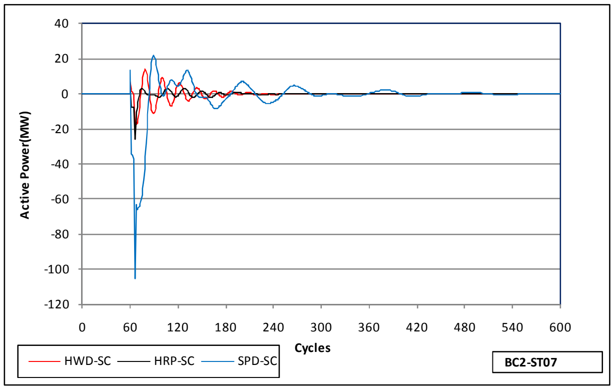
3.1.7 BC2-ST07: Three Phase Fault at Stony Brook 230 kV on line to Bay d'Espoir (TL204)

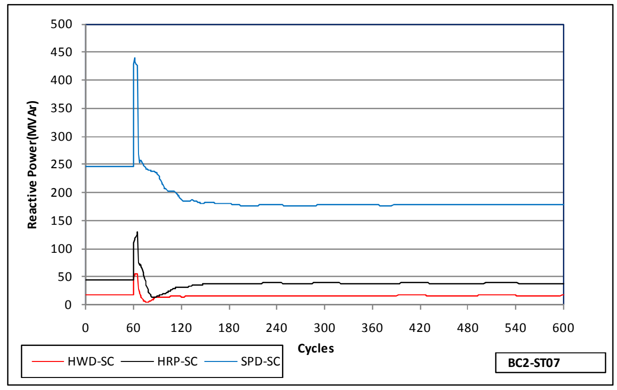
The voltage depression at Bottom Brook was severe enough to result in blocking of the Maritime Link but did not cause interruption of the Island Link. The system recovered quickly. The temporary over-voltage at Bottom brook was 120% for a few cycles. The results are shown in Figure 3-13.

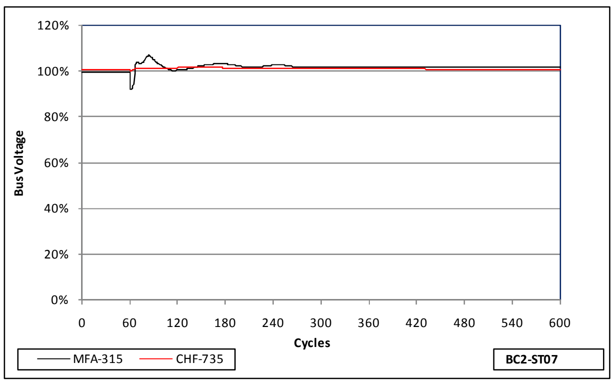
Figure 3-13: BC2-ST07, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Stony Brook 230 kV on line to Bay d'Espoir (TL204)

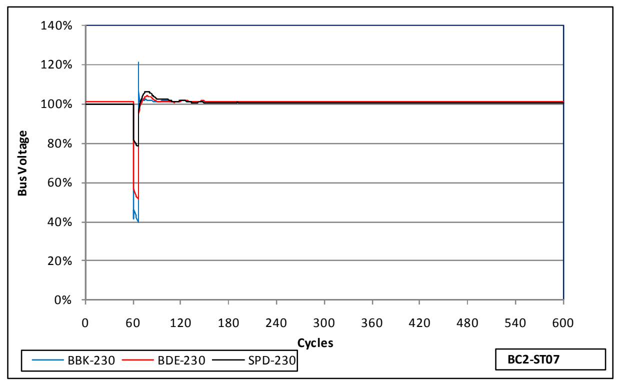


SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	49







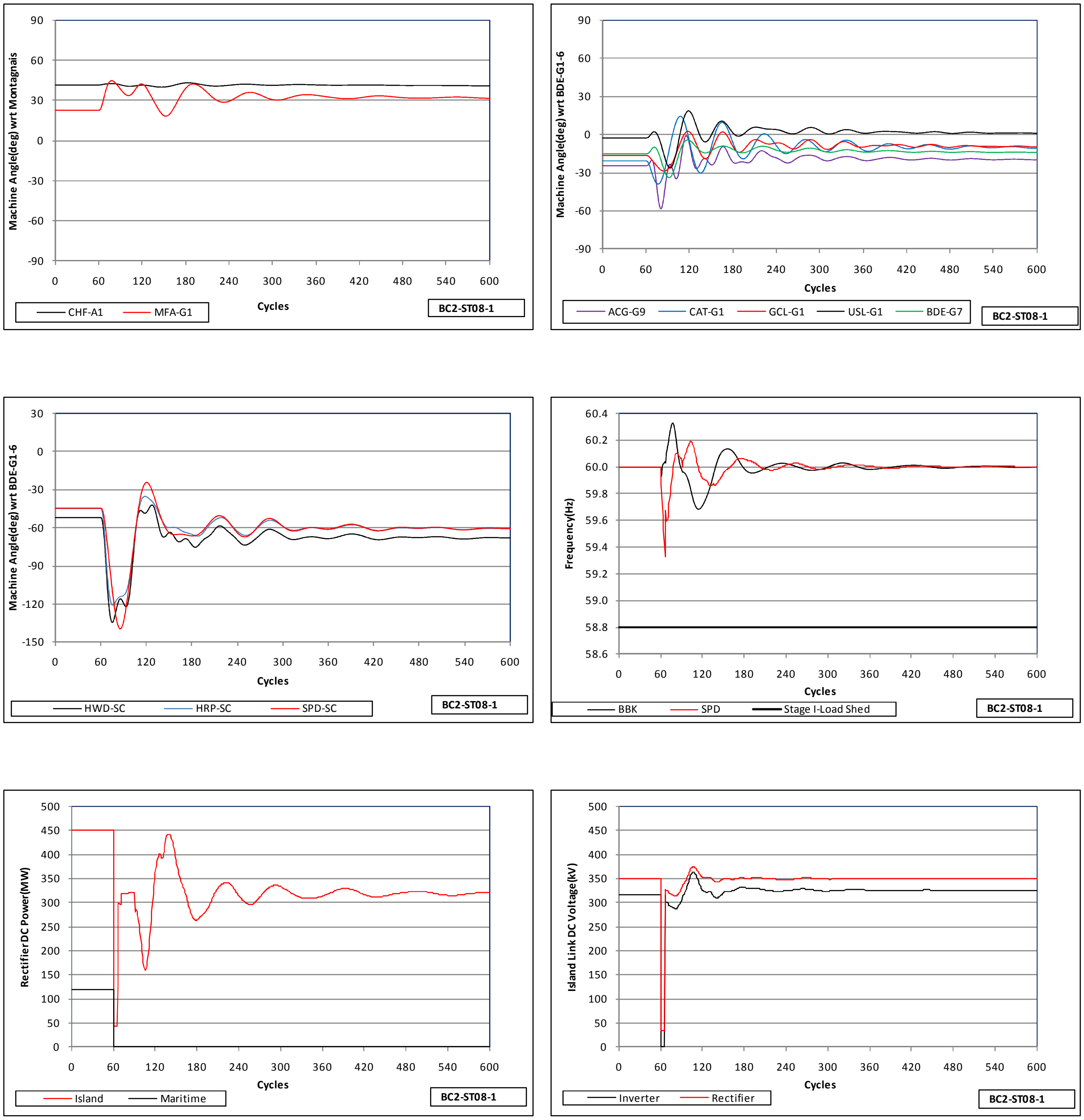


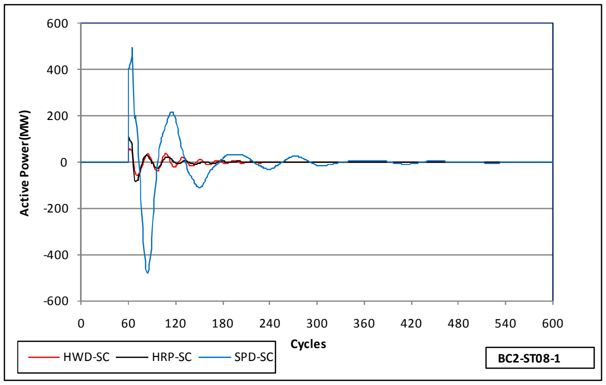
3.1.8 BC2-ST08: Three Phase Fault at Bay d'Espoir 230 kV on line to Sunnyside (TL202)

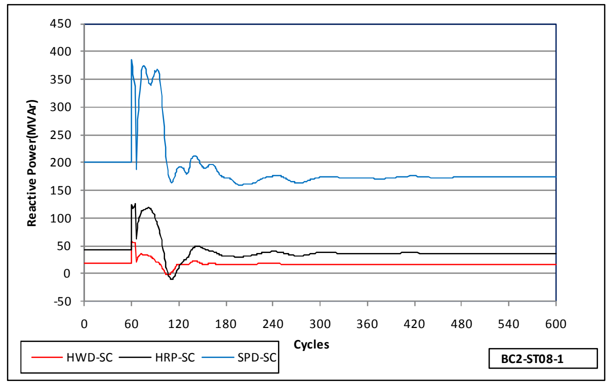
This case was similar to, though not as severe as, the case of a fault at Bay d'Espoir on the line to Western Avalon. As with the fault at Bay d'Espoir on the line to Western Avalon however, it was necessary to either:

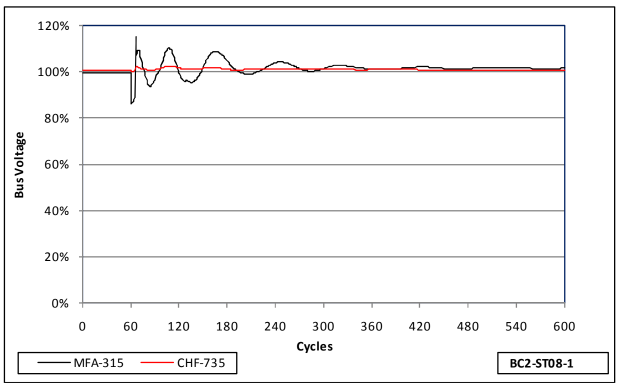
- increase the high-inertia synchronous condenser at Soldiers Pond to 450 MVAr and connect the third synchronous condenser at Holyrood, or
- install a ±250 MVAr SVC at Bay d'Espoir and connect the third synchronous condenser at Holyrood, to avoid a voltage reduction at Soldiers Pond following the fault clearance. The results with 450 MVAr of high-inertia synchronous condensers at Soldiers Pond are shown in Figure 3-14.

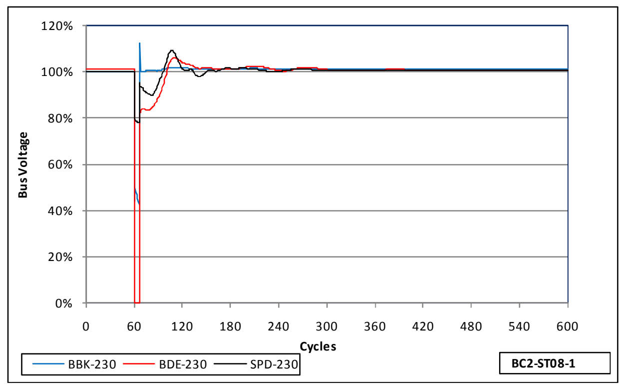
Figure 3-14: BC2-ST08-1, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV on line to Sunnyside (TL202)




Active Power(MW)
600
400
200
0
-200
-400
-600
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC HRP-SC SPD-SC
BC2-ST08-1


Reactive Power(MVAr)
450
400
350
300
250
200
150
100
50
0
-50
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC HRP-SC SPD-SC
BC2-ST08-1


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
MFA-315 CHF-735
BC2-ST08-1

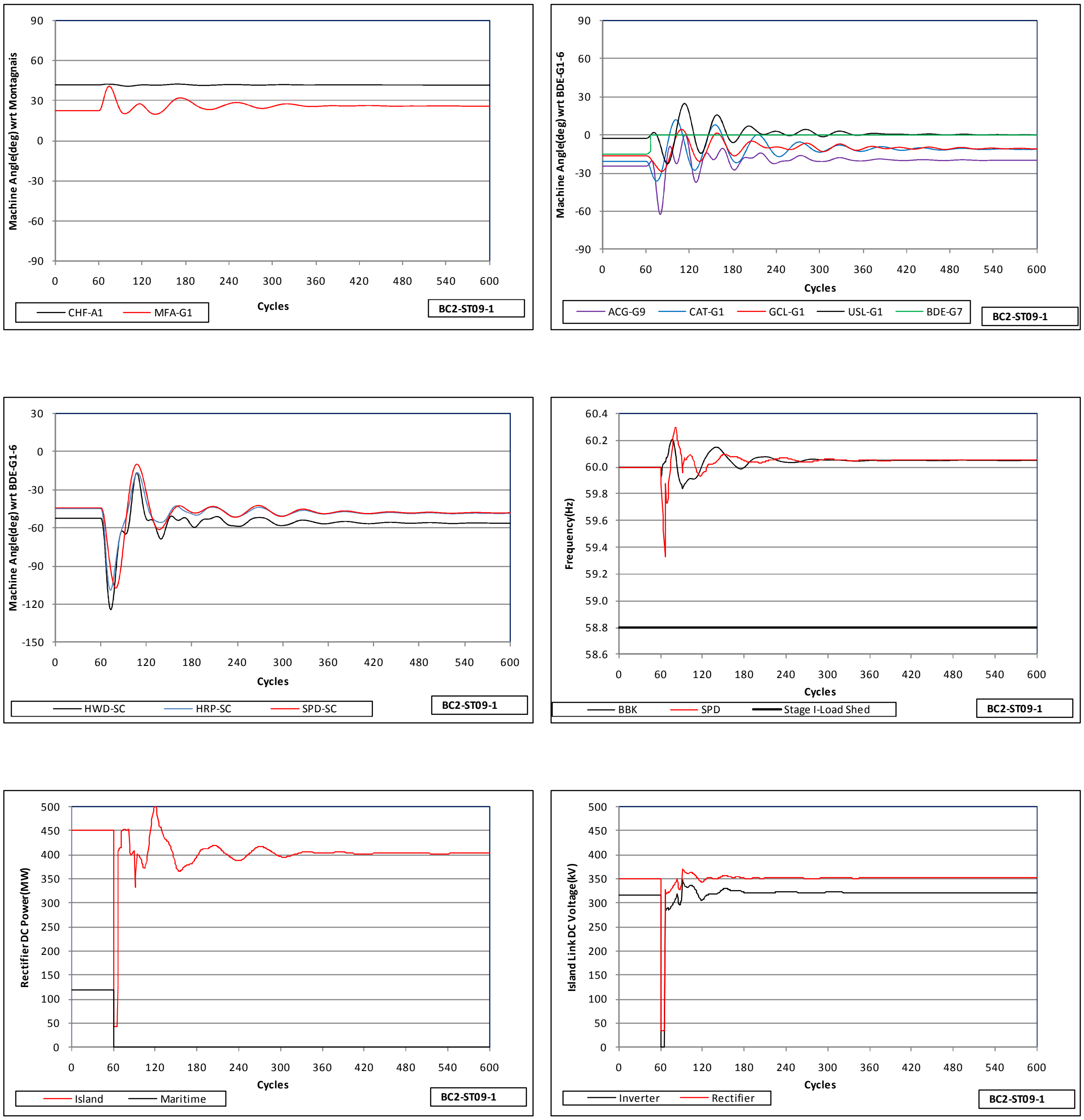

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
BBK-230 BDE-230 SPD-230
BC2-ST08-1

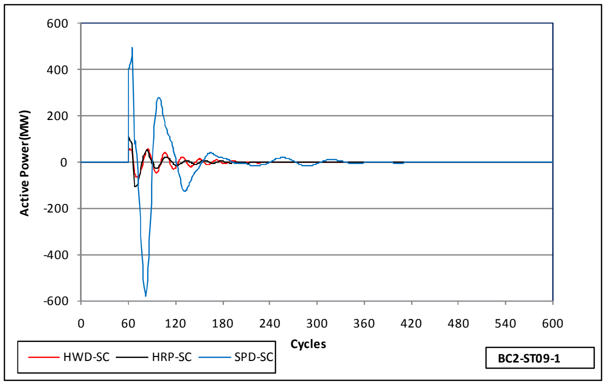
3.1.9 BC2-ST09: Three Phase Fault at Bay d'Espoir 230 kV-Generator Outage G7

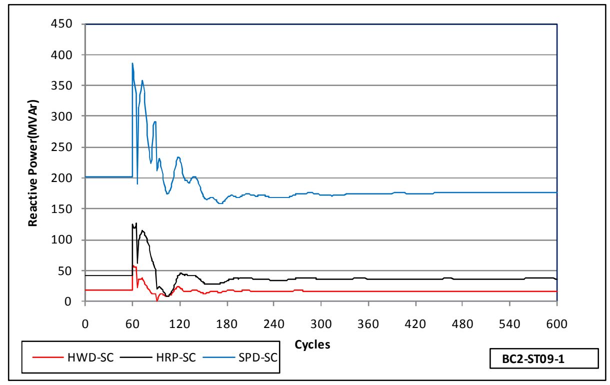
This case, shown in Figure 3-15, considered a 6-cycle, 3-phase fault at Bay d'Espoir 230 kV that resulted in the loss of the largest generator on the Island system (unit G7). As with other faults at Bay d'Espoir, a commutation failure can occur at the inverter of the LIL and the export to Nova Scotia is reduced to zero due to the voltage depression at Bottom Brook, and it was necessary to either:

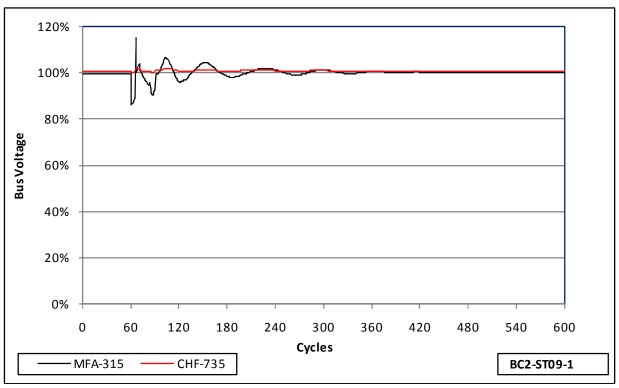
- increase the high-inertia synchronous condenser at Soldiers Pond to 450 MVAr and connect the third synchronous condenser at Holyrood, or
- install a ±250 MVAr SVC at Bay d'Espoir and connect the third synchronous condenser at Holyrood.

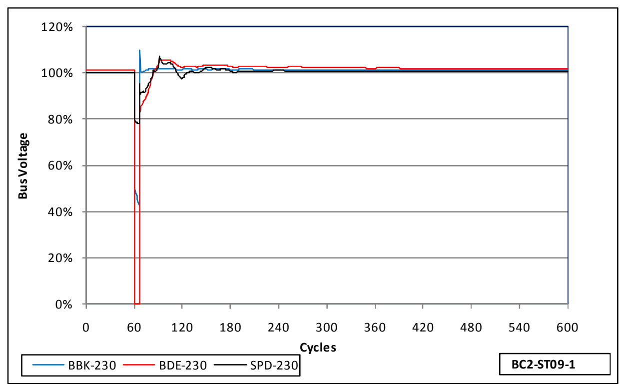
Figure 3-15: BC2-ST09-1, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV-Generator Outage G7 450MVAr-SC at Soldiers Pond+3-SC at Holyrood




600
400
200
0
-200
-400
-600
Active Power(MW)
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST09-1


450
400
350
300
250
200
150
100
50
0
Reactive Power(MVAr)
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST09-1


120%
100%
80%
60%
40%
20%
0%
Bus Voltage
0 60 120 180 240 300 360 420 480 540 600
Cycles
MFA-315
CHF-735
BC2-ST09-1


120%
100%
80%
60%
40%
20%
0%
Bus Voltage
0 60 120 180 240 300 360 420 480 540 600
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST09-1

3.2 Spring/Fall Intermediate Load Conditions

The forecast load on the Island system for the intermediate load level corresponding to Spring and Fall in 2017-18 is 1,100 MW. The first scenario to be examined under these conditions was BC-7, since this scenario involves the rated transfer across the Island Link (900 MW from Muskrat Falls) and the maximum transfer across the Maritime Link (500 MW from Bottom Brook). Figure A-2 in Appendix A shows the load flow of the initial conditions.

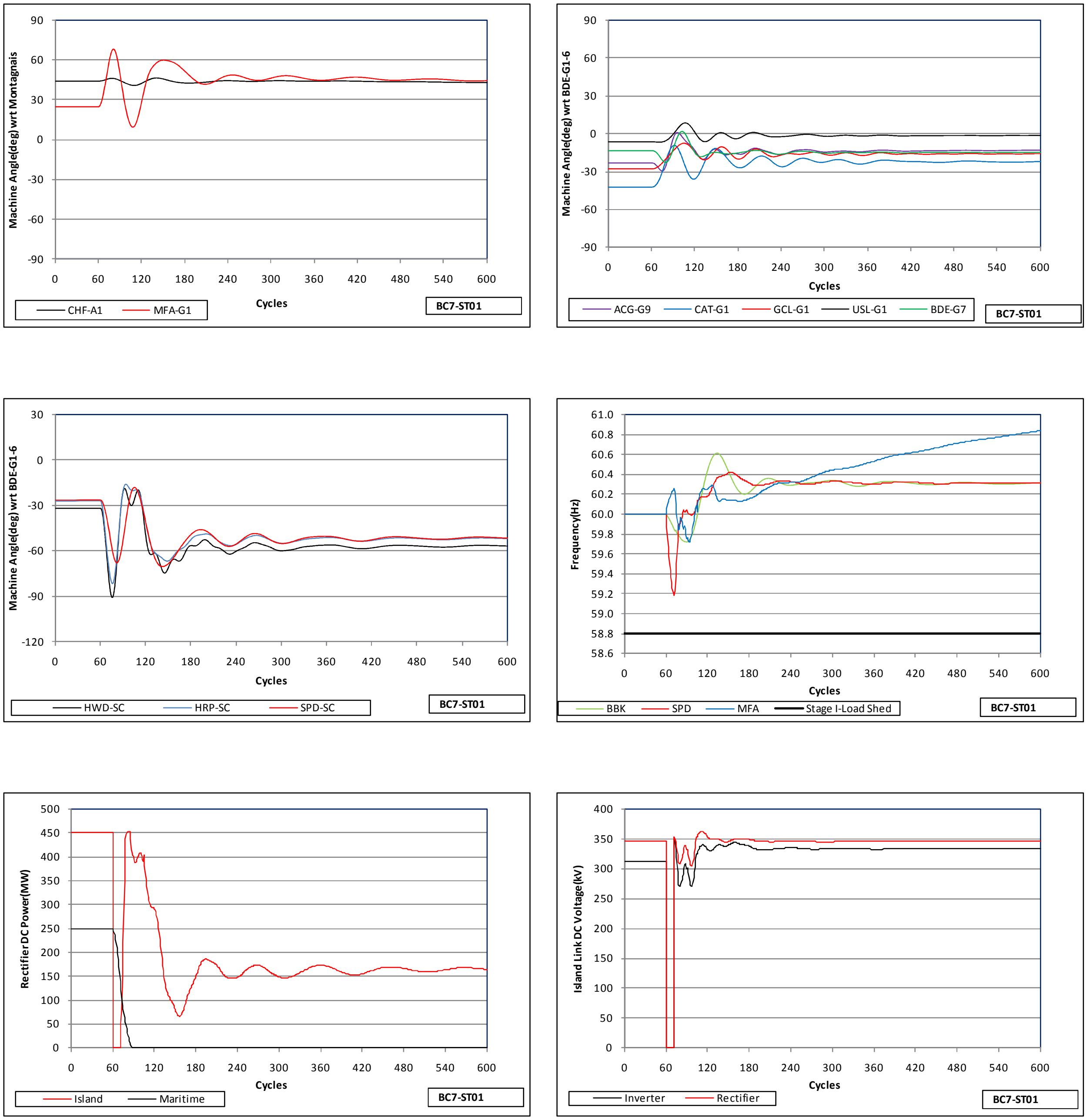
The same fault cases were examined for this load level as for the peak load level.

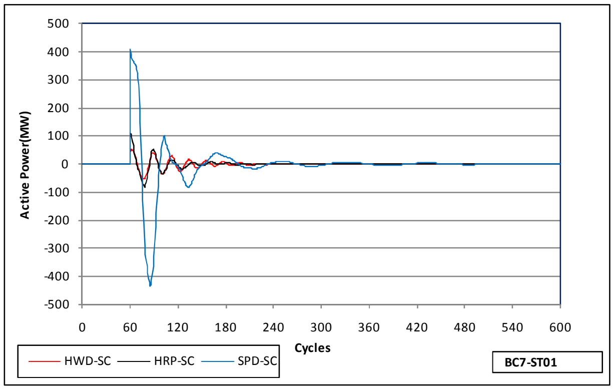
3.2.1 BC7-ST01: Temporary Bipole Fault on the Island Link

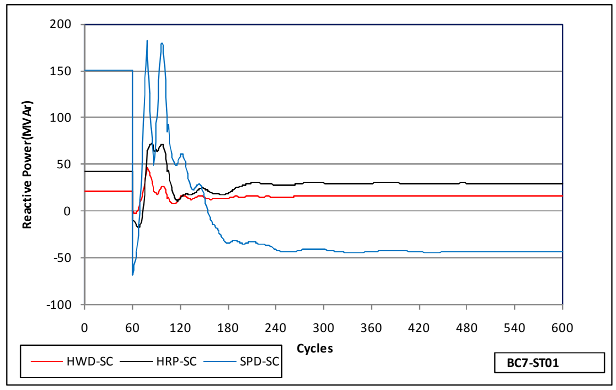
The results for this case are shown in Figure 3-16.

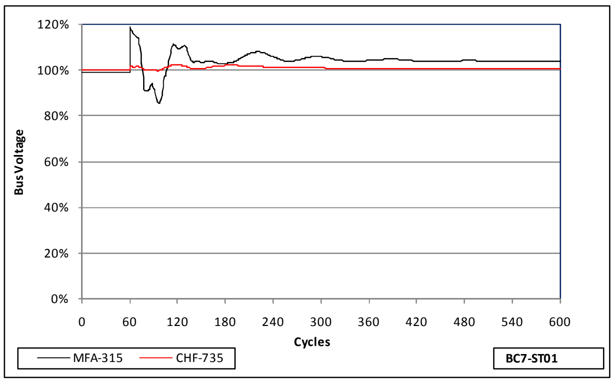
The voltage and frequency depression at Bottom Brook resulted in a ramping down of the Maritime export from 500 MW to zero. The Island Link returned to full power shortly after fault clearance as in previous cases, and the enabling of the Island Link frequency controller after 500 ms resulted in a reduction of the dc power over the Island Link to approximately 320 MW due to the loss of the Maritime export. The frequency at Soldiers Pond stabilized at approximately 60.3 Hz and the system returned to stable operation quickly.

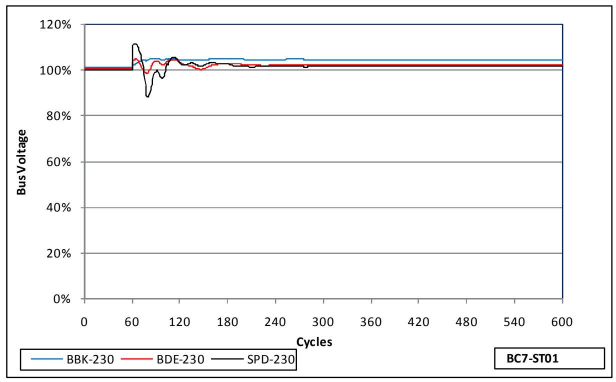
Figure 3-16: BC7-ST01, Intermediate/Island Link 900 MW/Maritime Link 500 MW Temporary Bipole Fault on Island Link




Active Power(MW)
500
400
300
200
100
0
-100
-200
-300
-400
-500
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC HRP-SC SPD-SC
BC7-ST01


Reactive Power(MVAr)
200
150
100
50
0
-50
-100
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC HRP-SC SPD-SC
BC7-ST01


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
MFA-315 CHF-735
BC7-ST01


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
BBK-230 BDE-230 SPD-230
BC7-ST01

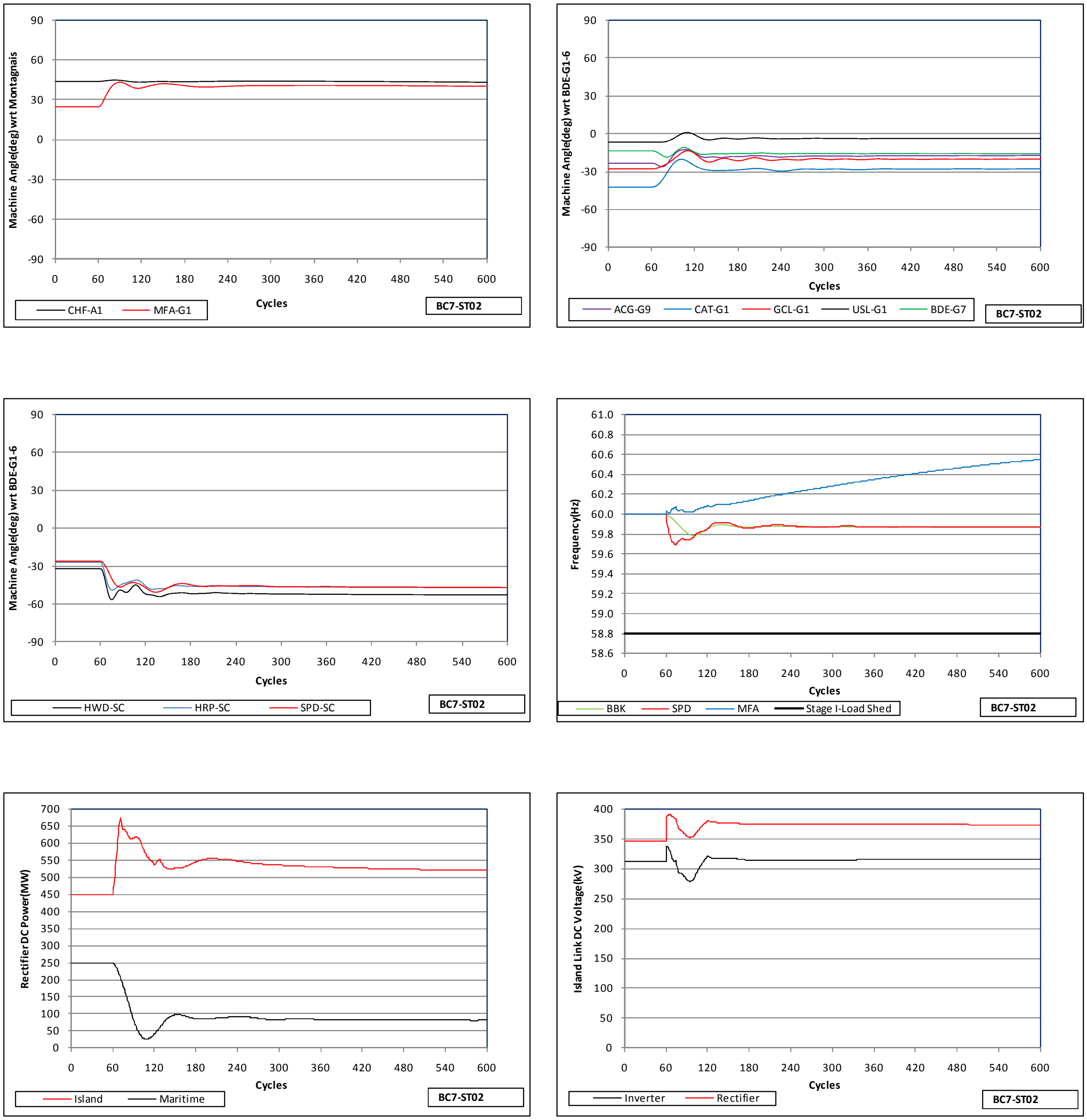
3.2.2 BC7-ST02: Permanent Pole Fault on the Island Link

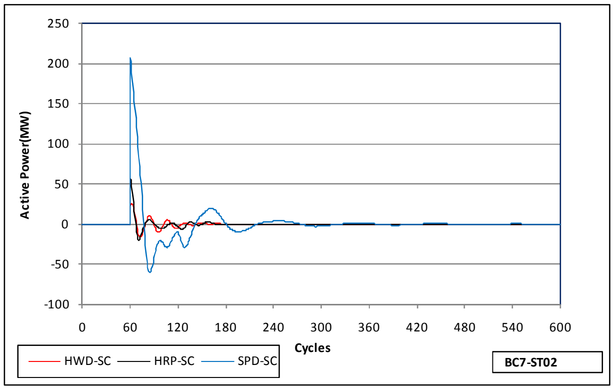
The results for this case are shown in Figure 3-17.

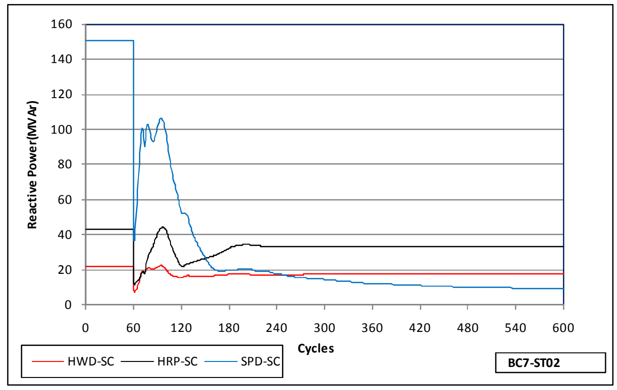
This case was seen to be less severe than the same fault in the BC2 Scenario in that the Maritime Link was not reduced to zero but fell to a value of approximately 160 MW from its initial value of 500 MW. The Island Link healthy pole was ramped up to a value of approximately 520 MW from its initial value of 450 MW (a 115% overload). The frequency at Soldiers Pond stabilized at approximately 59.85 Hz.

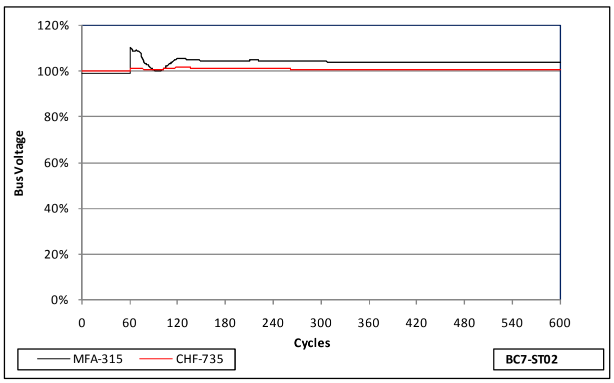
Once the system has settled down, it would be possible to manually reschedule the Island Link up to 675 MW (150% of its rated value) to allow the Maritime export to be increased from 160 MW to approximately 300 MW.

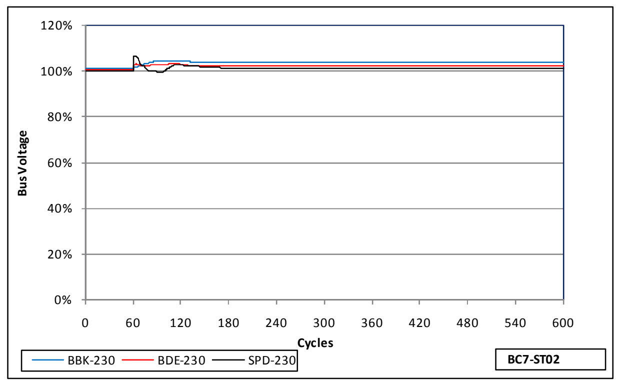
Figure 3-17: BC7-ST02, Intermediate/Island Link 900 MW/Maritime Link 500 MW Permanent Pole Outage on Island Link




Active Power(MW)
250
200
150
100
50
0
-50
-100
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC HRP-SC SPD-SC
BC7-ST02


Reactive Power(MVAr)
160
140
120
100
80
60
40
20
0
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC HRP-SC SPD-SC
BC7-ST02


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
MFA-315 CHF-735
BC7-ST02

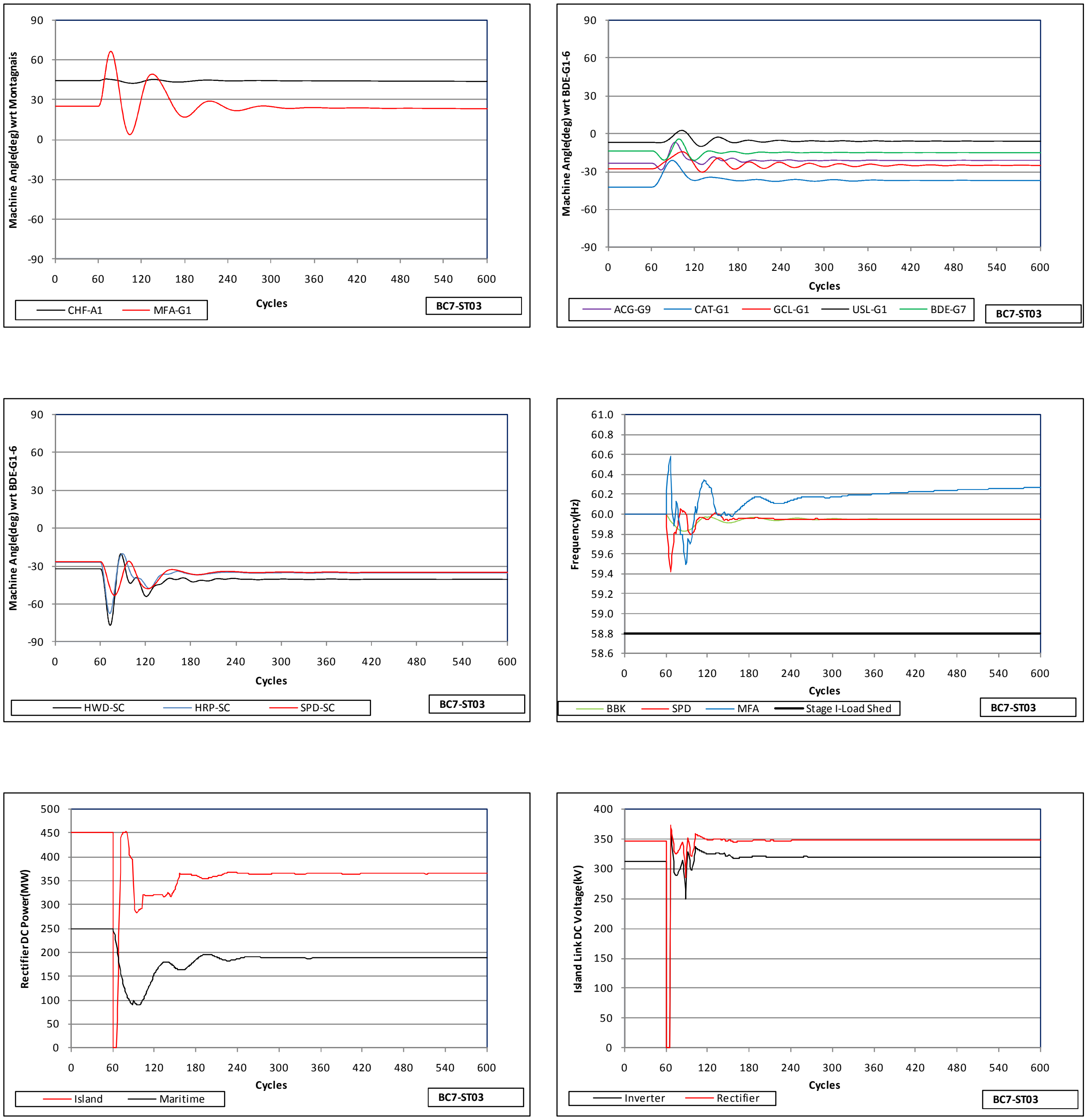

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
BBK-230 BDE-230 SPD-230
BC7-ST02

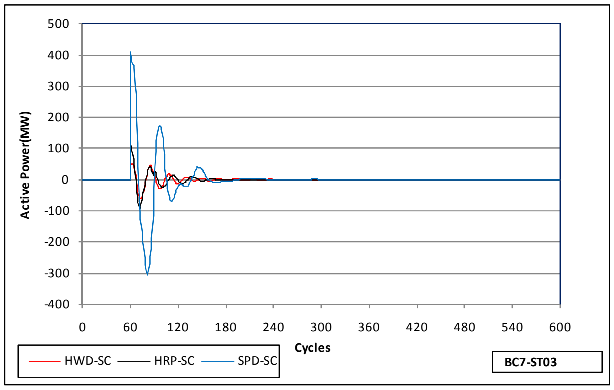
3.2.3 BC7-ST03: Three Phase Fault at Muskrat Falls 315 kV on line to Churchill Falls

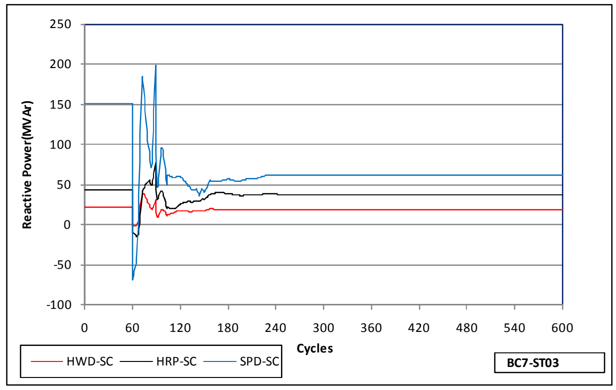
As with the permanent pole outage on the Island Link, this case (shown in Figure 3-18) was not as severe as the same fault under Scenario BC2. The Maritime Link did not fall to a zero export and was able to recover to an export level of approximately 380 MW, the Island Link decreasing from 900 MW to approximately 720 MW following the introduction of the frequency controller 500 ms following the fault. The Island frequency stabilized at just below 60 Hz.

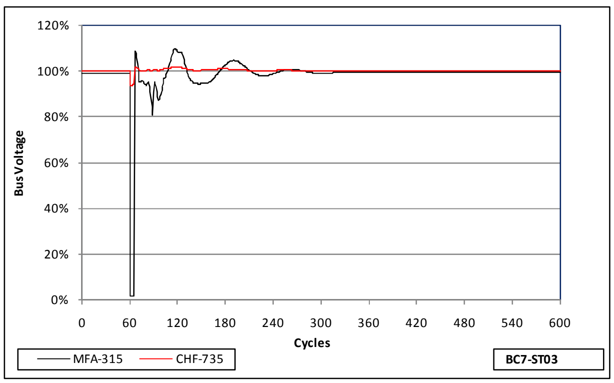
SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	63

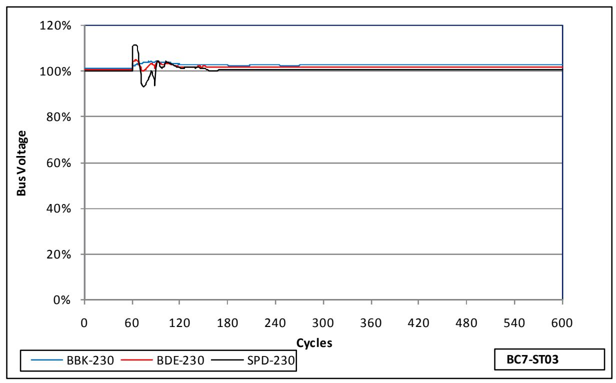
Figure 3-18: BC7-ST03, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Muskrat Falls 315 kV on line to Churchill Falls




Active Power(MW)
500
400
300
200
100
0
-100
-200
-300
-400
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST03


Reactive Power(MVAr)
250
200
150
100
50
0
-50
-100
0 60 120 180 240 300 360 420 480 540 600
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST03


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
MFA-315
CHF-735
BC7-ST03

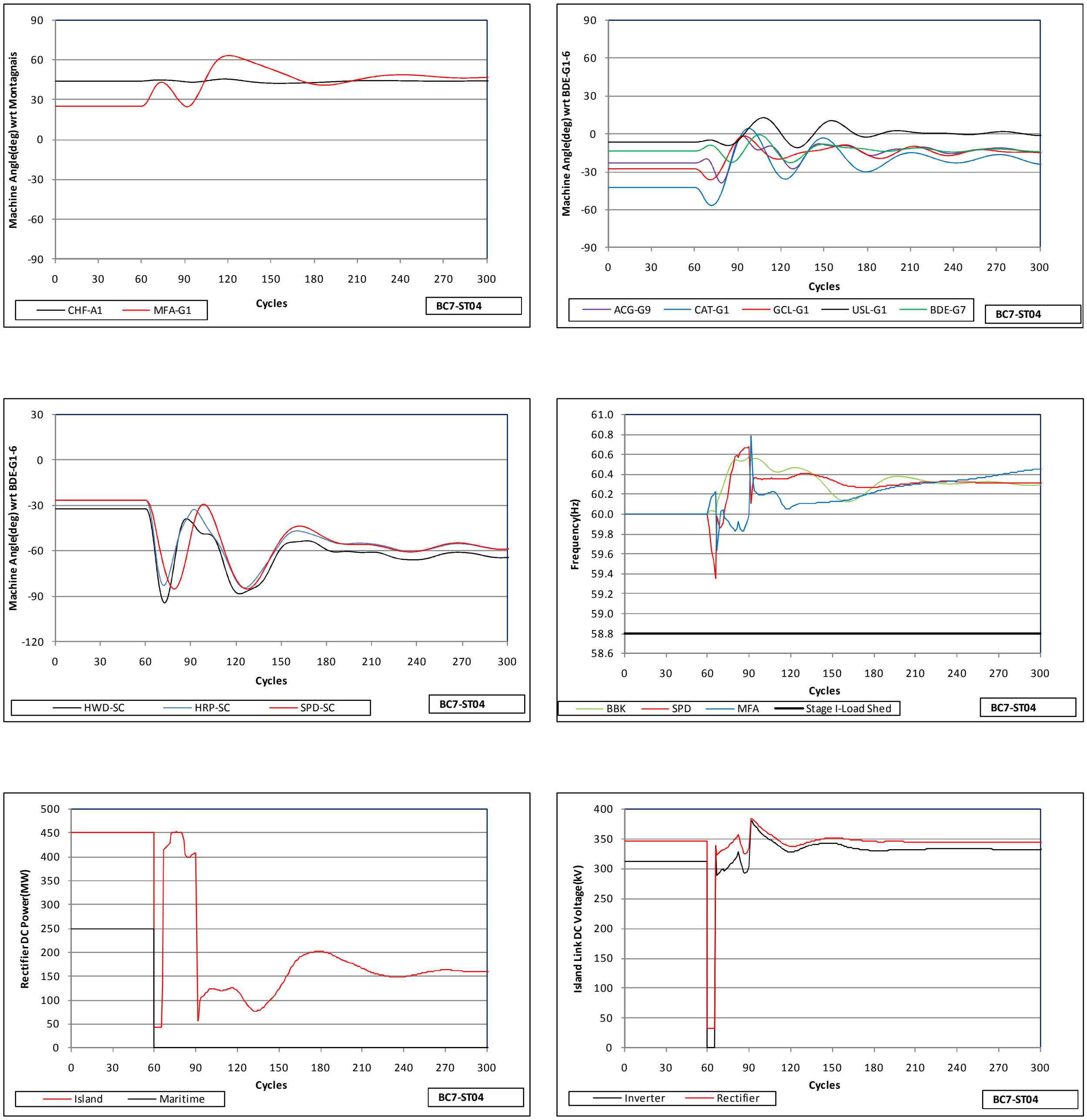

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 60 120 180 240 300 360 420 480 540 600
Cycles
BBK-230
BDE-230
SPD-230
BC7-ST03

3.2.4 BC7-ST04: Three Phase Fault at Bay d'Espoir 230 kV on line to Western Avalon

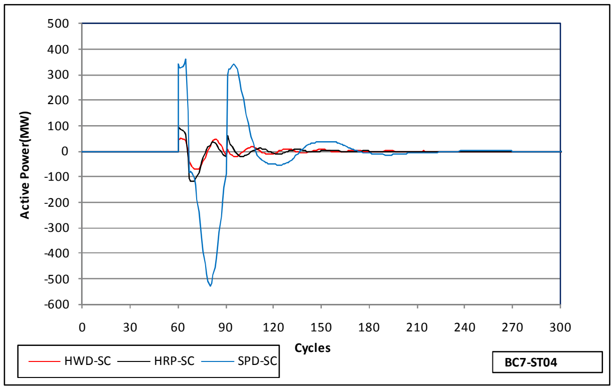
As with the permanent pole outage on the Island Link, this case (shown in Figure 3-19) was not as severe as the same fault under Scenario BC2. The Maritime Link still fell to a zero export due to the voltage depression at Bottom Brook. The Island Link decreased from 900 MW to approximately 300 MW as a result. The Island frequency stabilized at just 60.3 Hz.

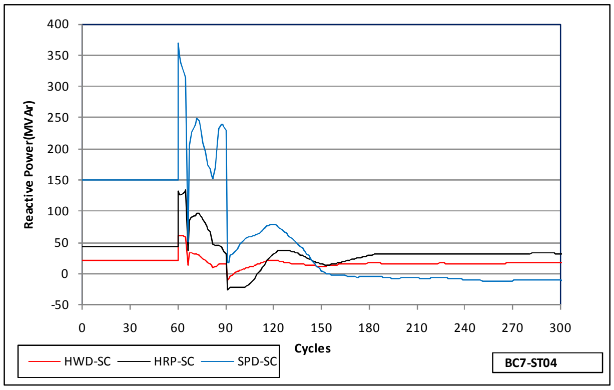
A temporary over-voltage was seen at Bottom Brook following the blocking of the Maritime Link and the subsequent fault clearance. This over-voltage which lasted only a few cycles was at a value of 125%.

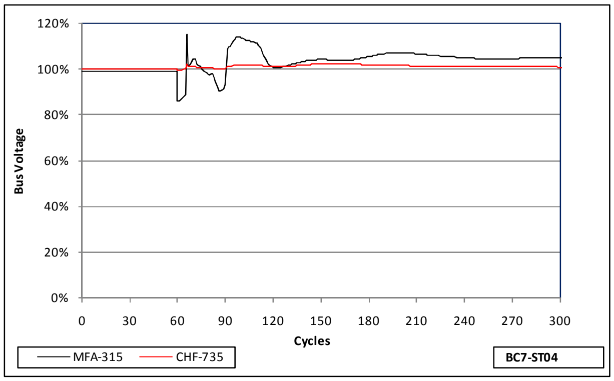
Figure 3-19: BC7-ST04, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV on line to Western Avalon

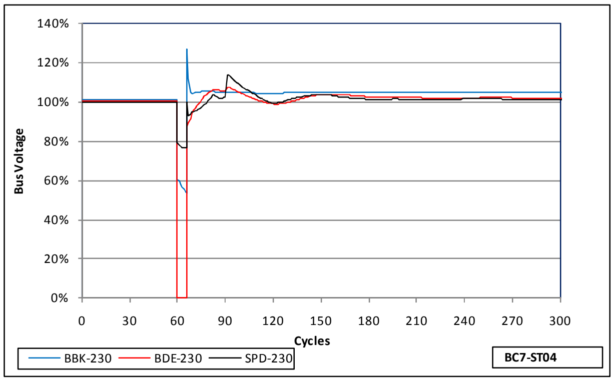


SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	67







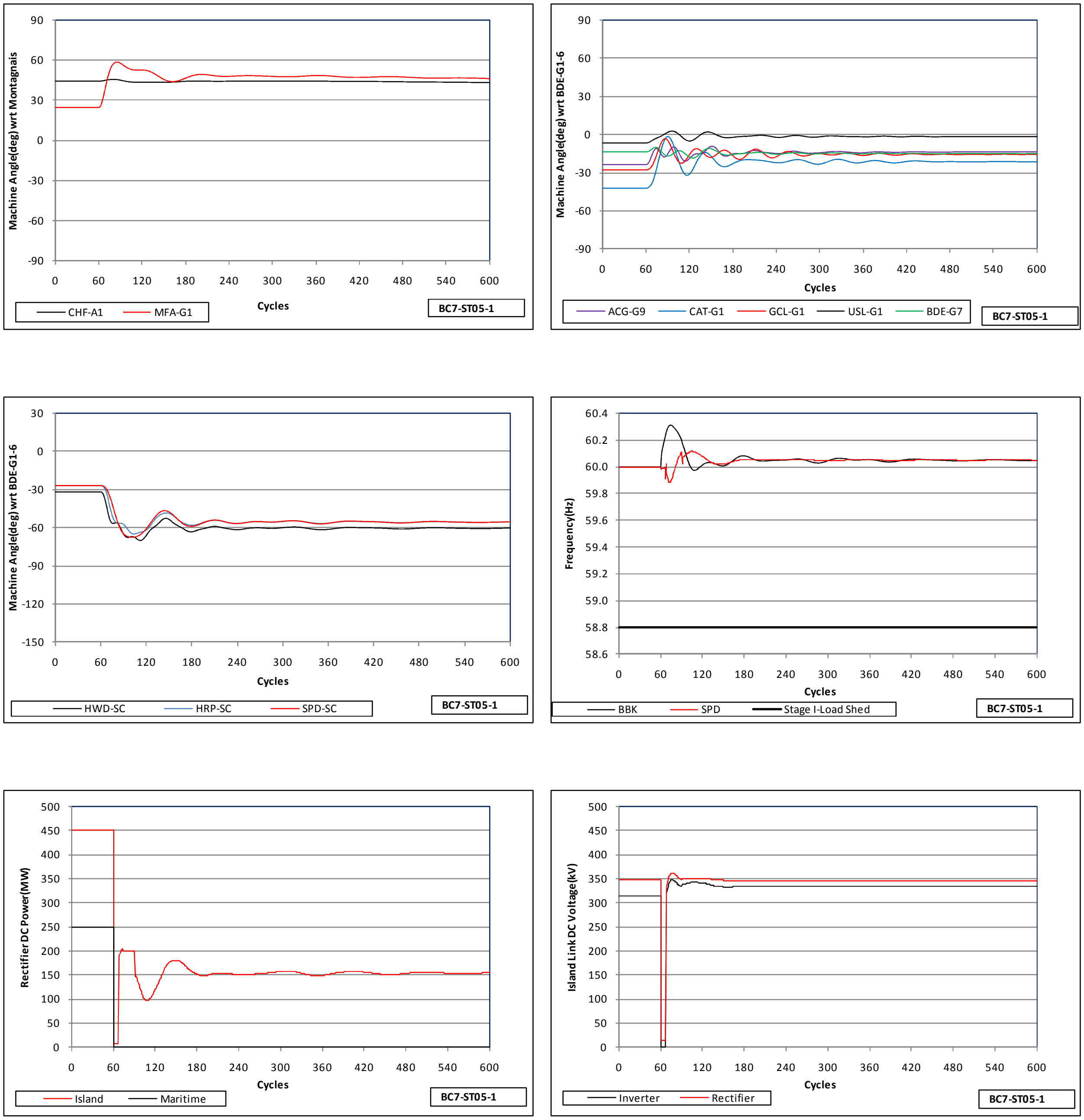


3.2.5 BC-7: Remaining Fault Cases

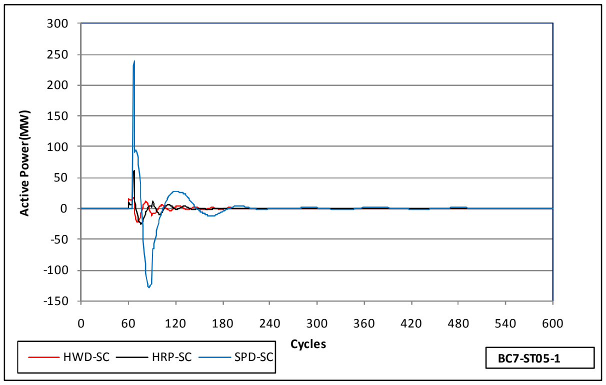
The remaining fault cases under BC-7 are shown in the following figures and indicate that the faults were not as severe as under Scenario BC-2 and that, in cases where the voltage depression at Bottom Brook was not too severe, the Maritime Link could be retained at a reduced power level. In general, for faults east of Bay d'Espoir the voltage at Bottom Brook remains high enough to allow continued operation of the Maritime Link. Faults at or west of Bay d'Espoir will result in a shutting down of the Maritime Link.

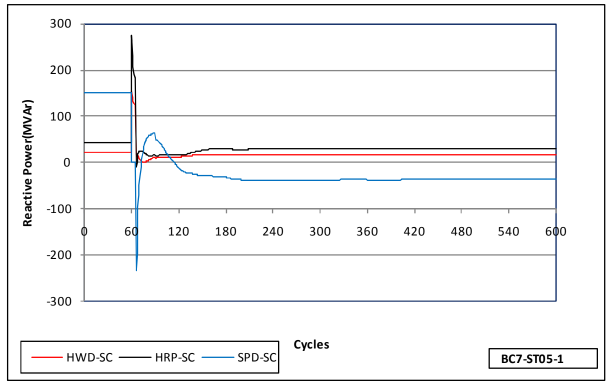
SNC•LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	69

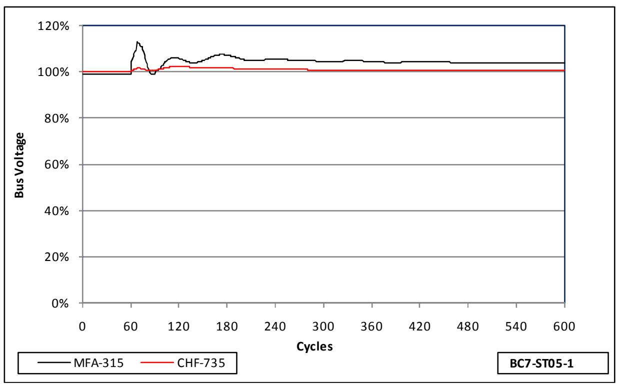
Figure 3-20: BC7-ST05-1, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Soldiers Pond 230 kV on line to Western Avalon (TL217W)



SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	70







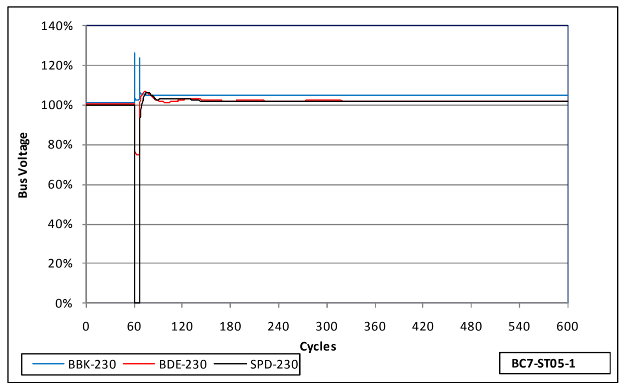
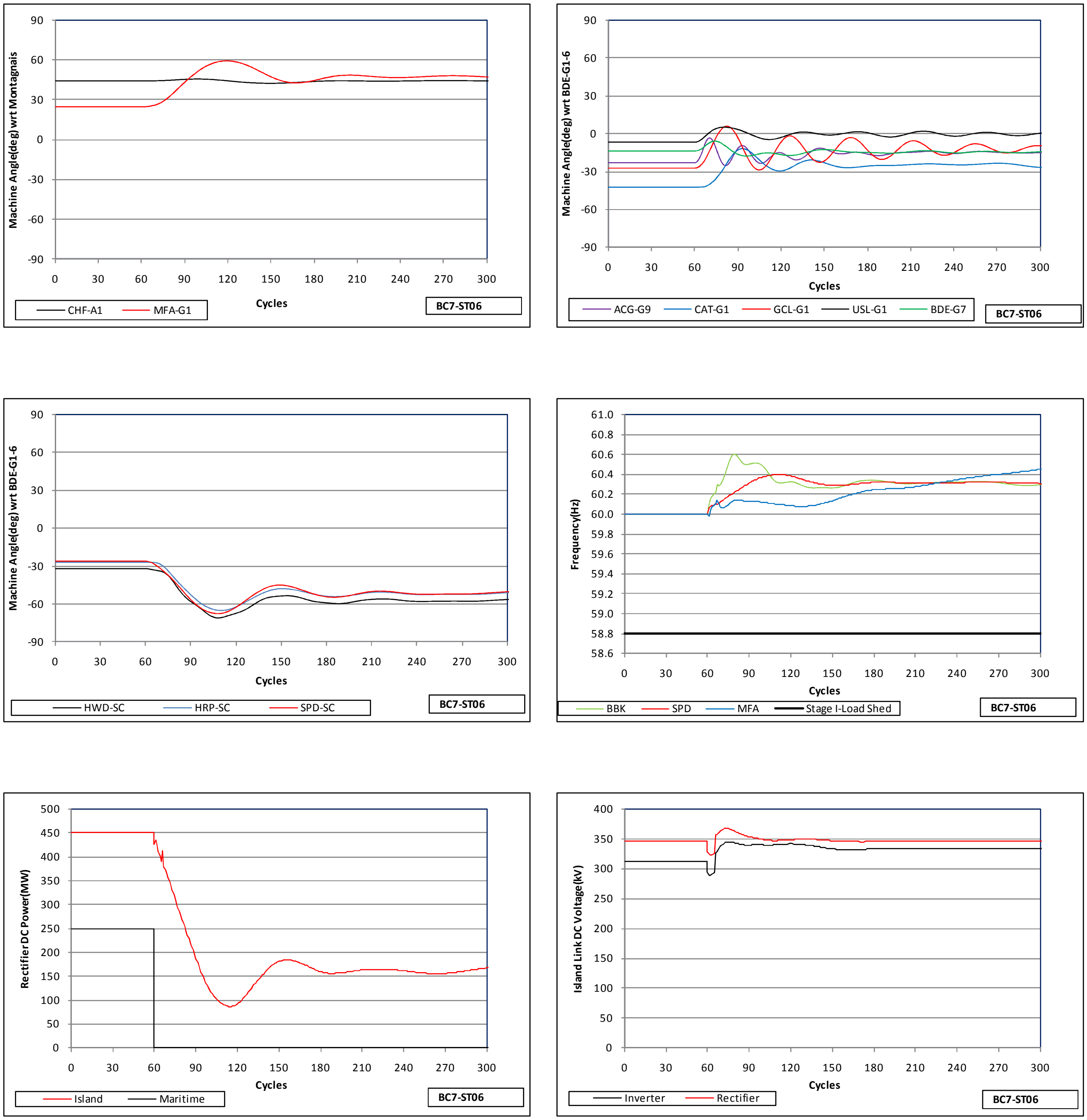
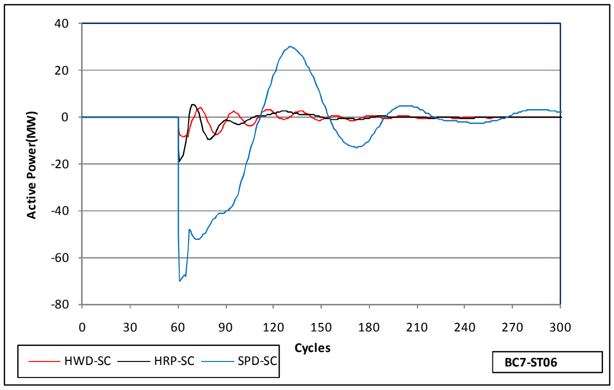
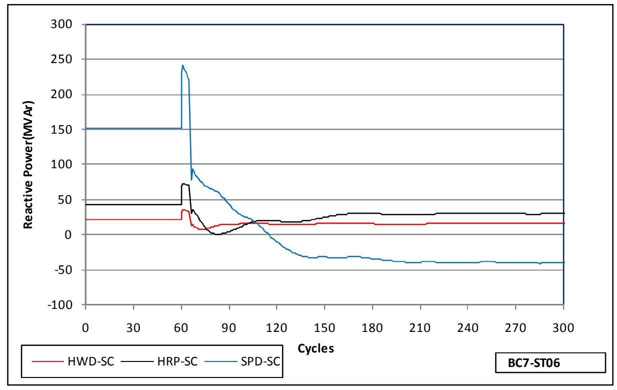
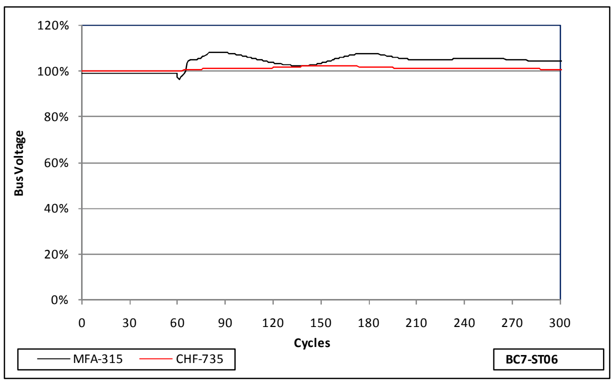


Figure 3-21: BC7-ST06, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Bottom Brook 230 kV on line to Granite Canal




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST06


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST06


Bus Voltage
Cycles
MFA-315
CHF-735
BC7-ST06

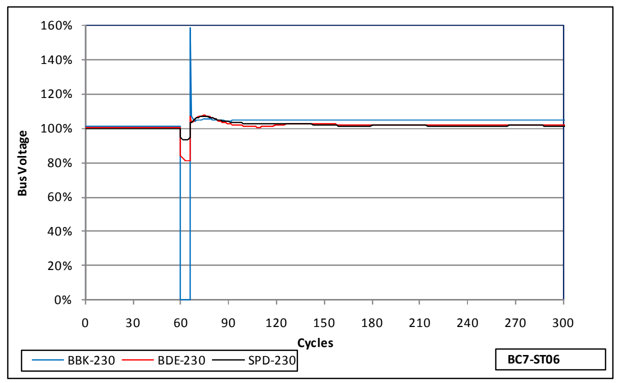
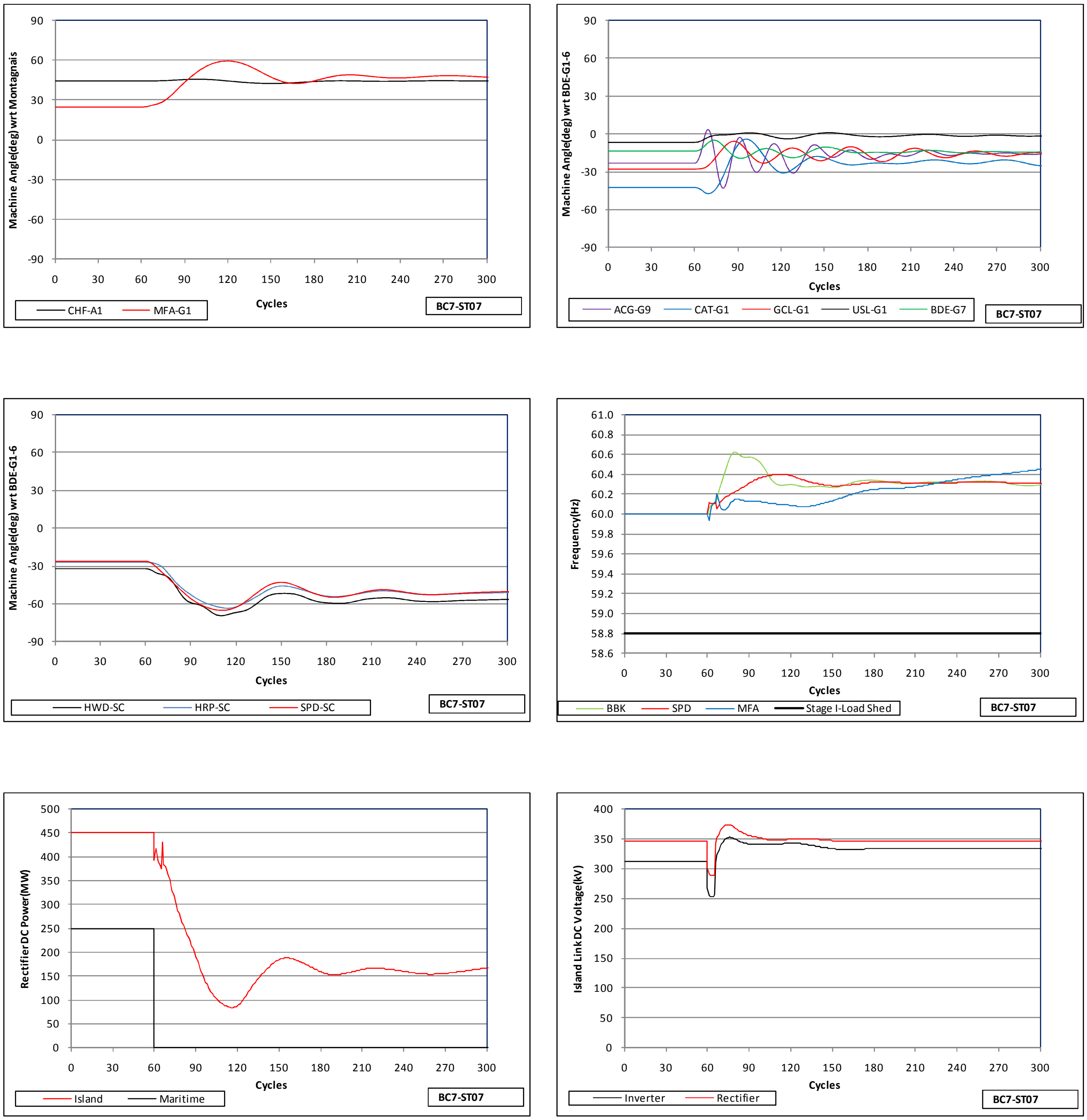
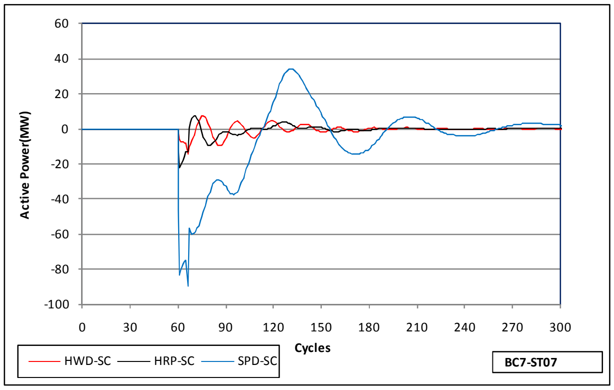
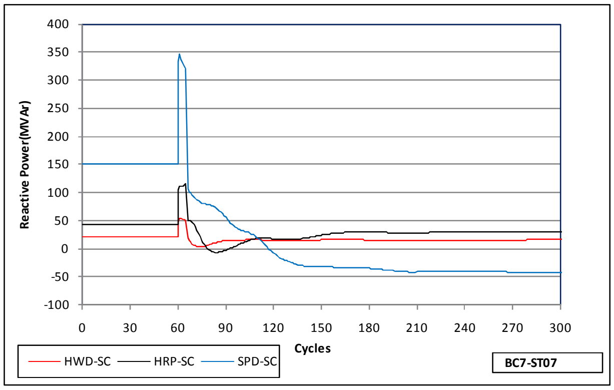
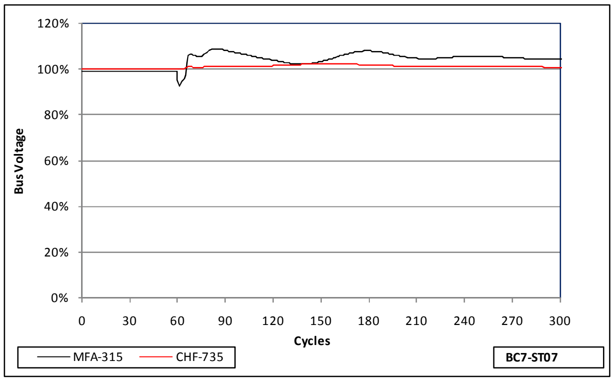

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC7-ST06

Figure 3-22: BC7-ST07, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Stony Brook 230 kV on line to Bay d'Espoir (TL204)




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST07


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST07


Bus Voltage
Cycles
MFA-315
CHF-735
BC7-ST07

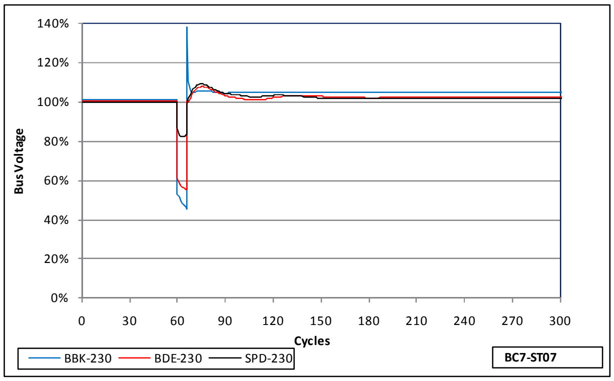
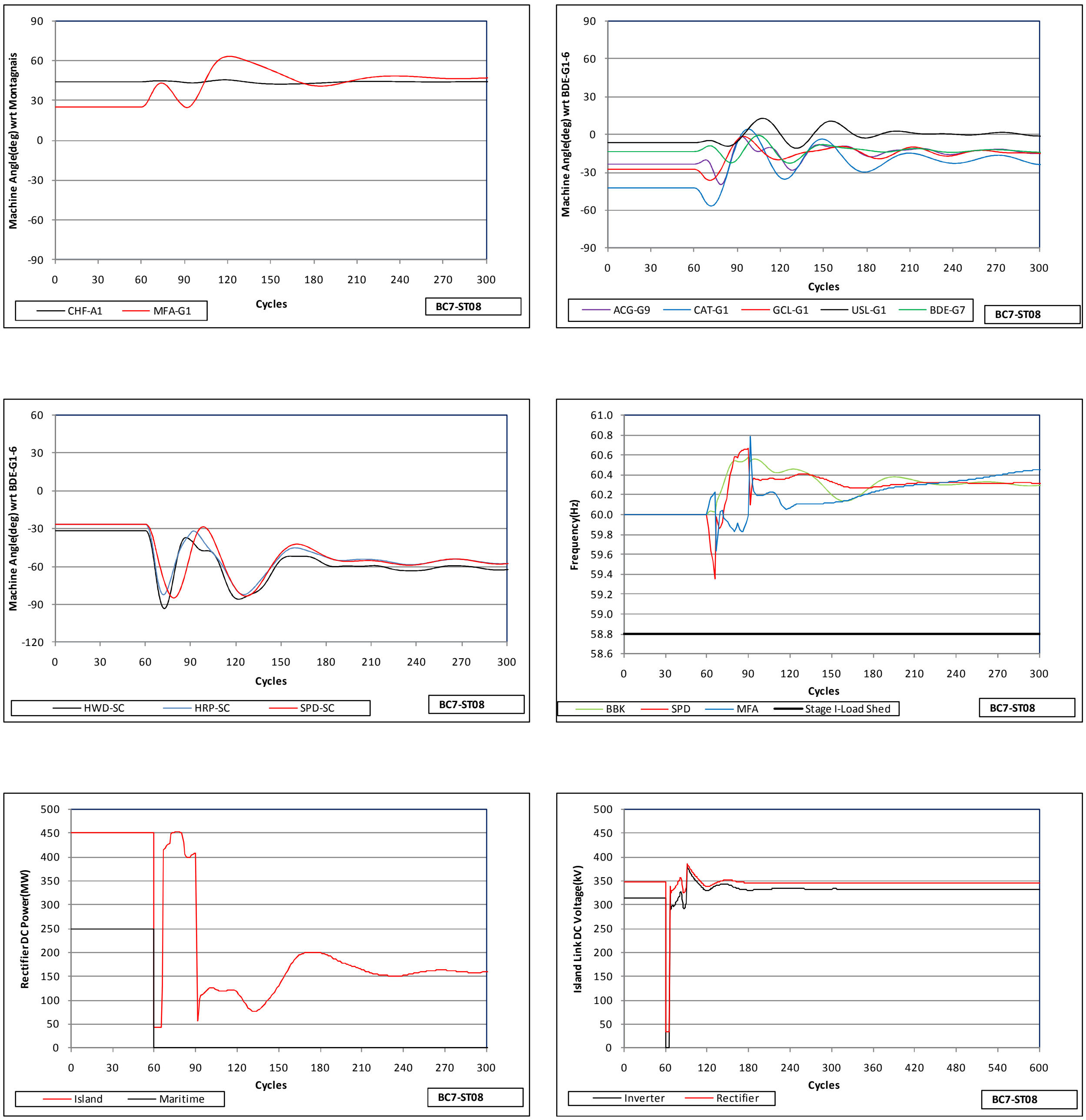
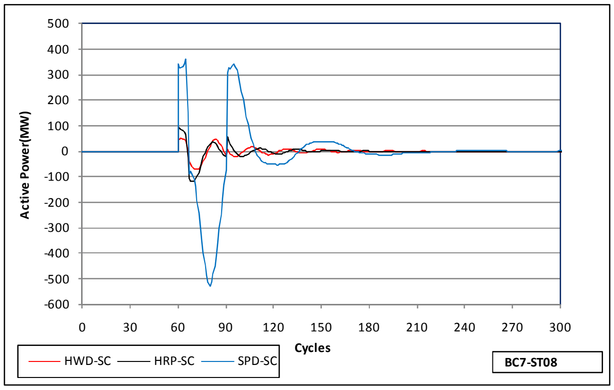
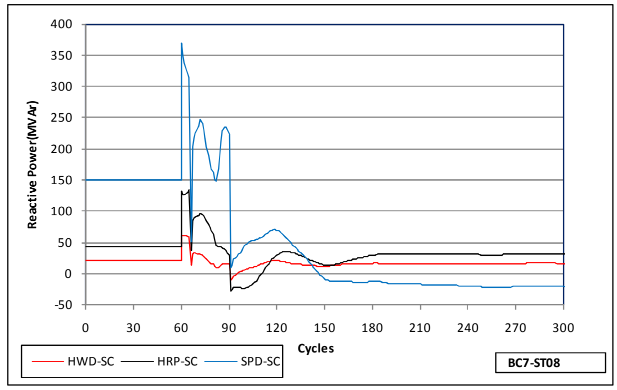
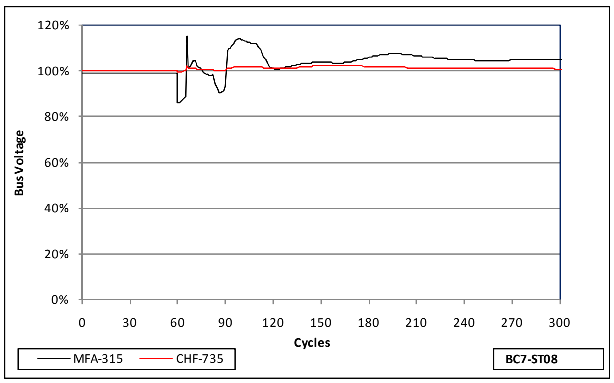

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC7-ST07

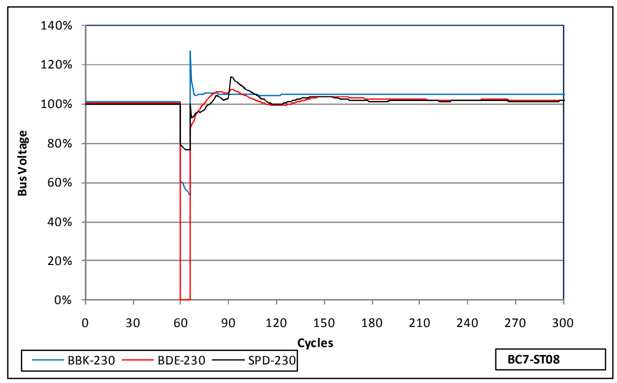
Figure 3-23: BC7-ST08, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV on line to Sunnyside (TL202)




Active Power(MW)
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
0
30
60
90
120
150
180
210
240
270
300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST08

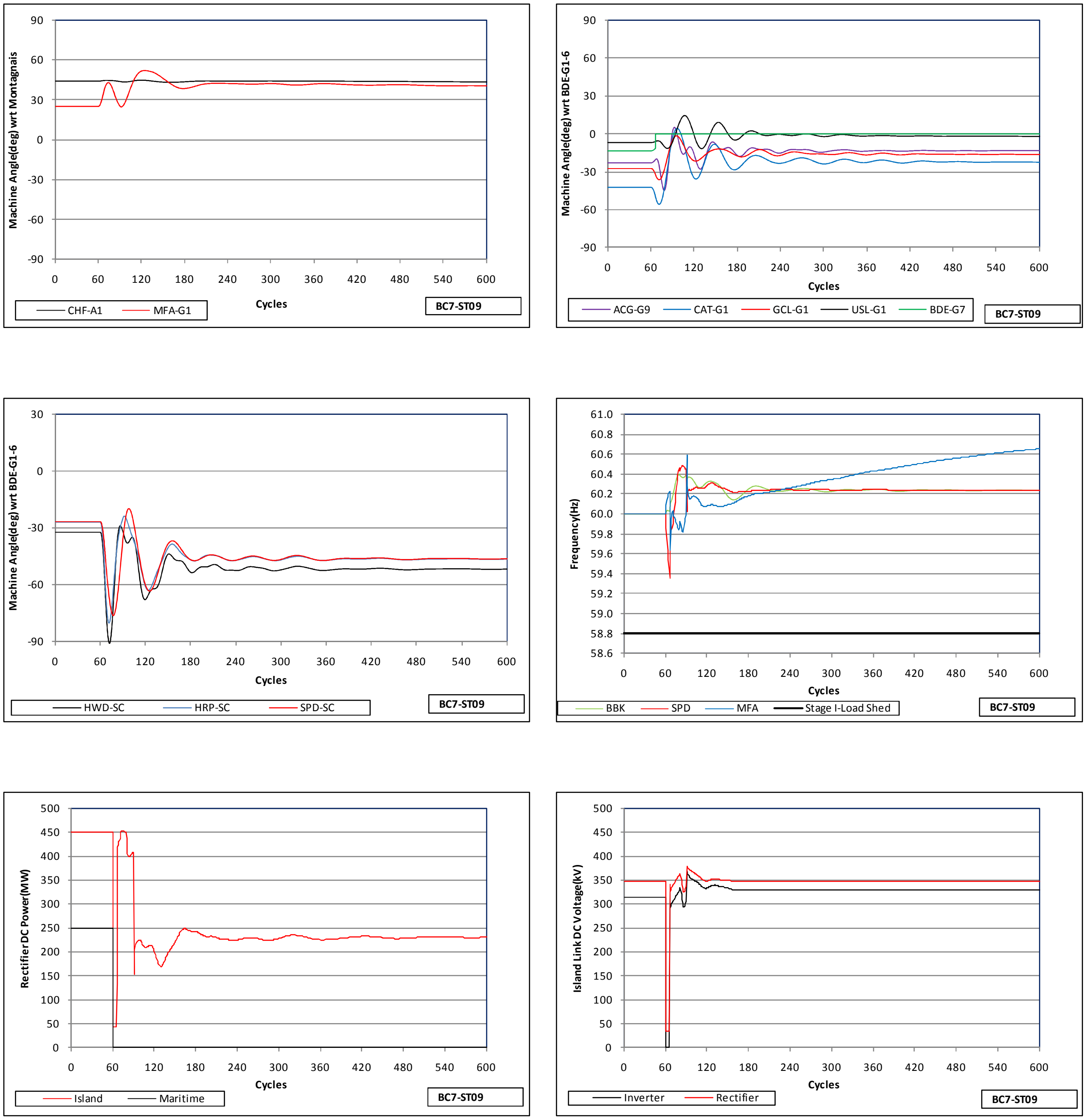

Reactive Power(MVAr)
400
350
300
250
200
150
100
50
0
-50
0
30
60
90
120
150
180
210
240
270
300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST08

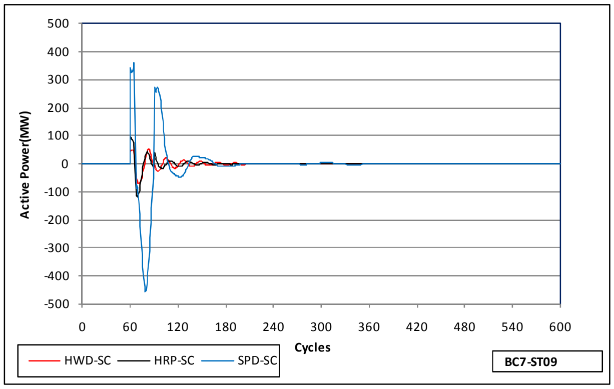

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0
30
60
90
120
150
180
210
240
270
300
Cycles
MFA-315
CHF-735
BC7-ST08

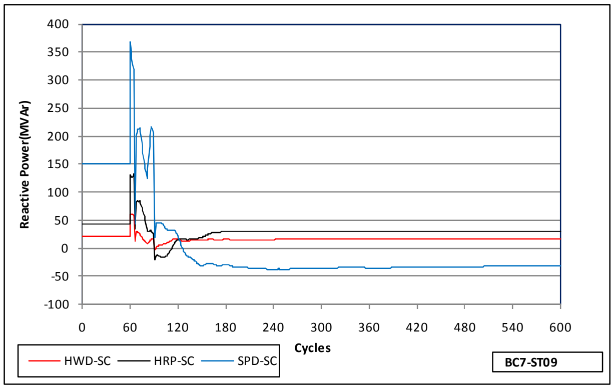

Bus Voltage
140%
120%
100%
80%
60%
40%
20%
0%
0
30
60
90
120
150
180
210
240
270
300
Cycles
BBK-230
BDE-230
SPD-230
BC7-ST08

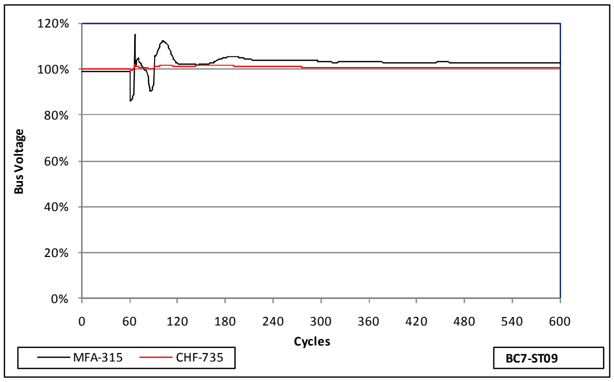
SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	77

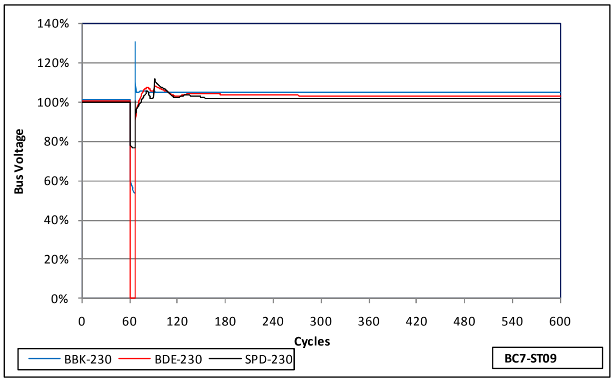
Figure 3-24: BC7-ST09, Intermediate/Island Link 900 MW/Maritime Link 500 MW 6-cycle, 3-phase Fault at Bay d'Espoir 230 kV-Generator Outage G7




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST09


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC7-ST09


Bus Voltage
Cycles
MFA-315
CHF-735
BC7-ST09

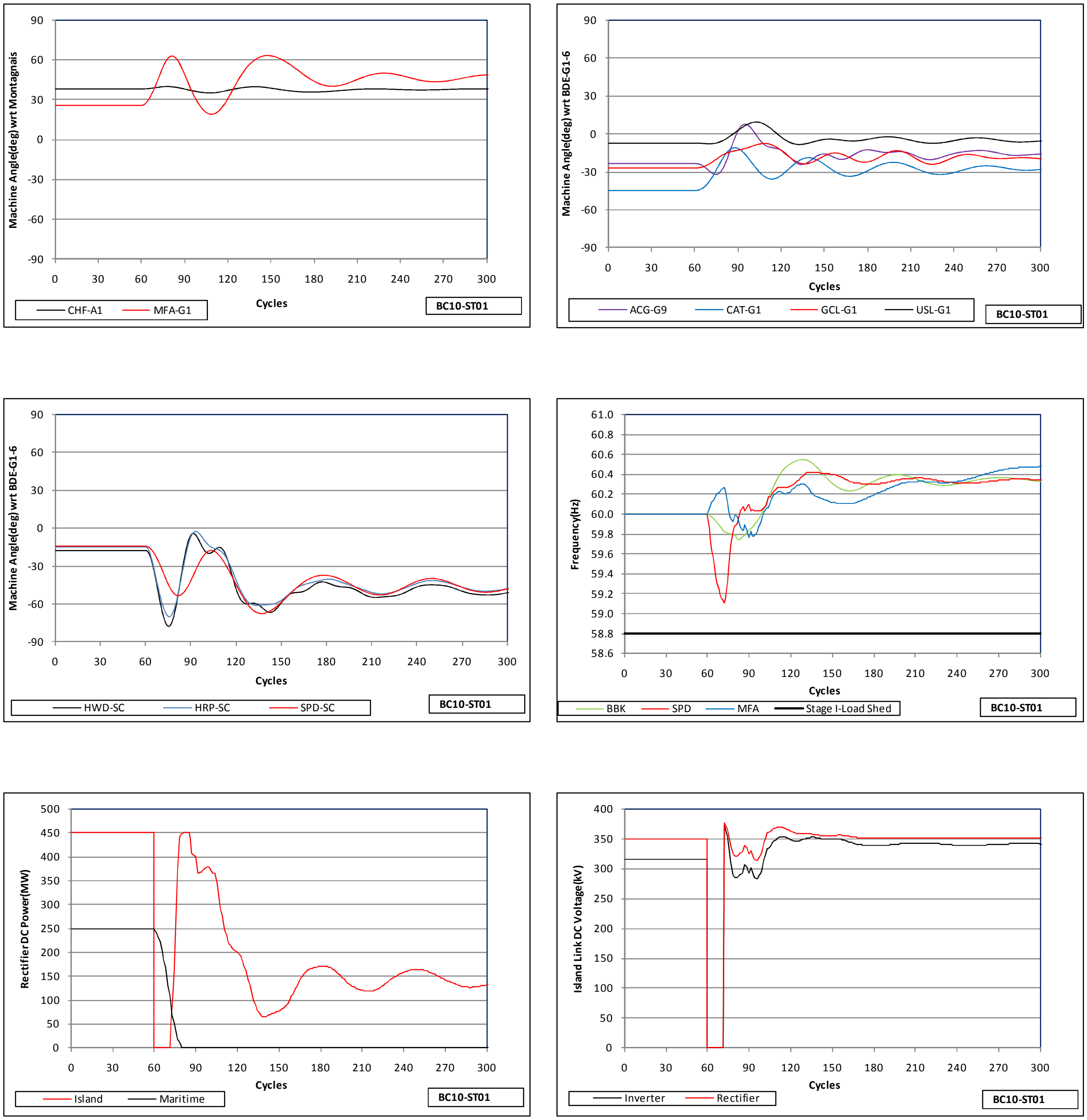

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC7-ST09

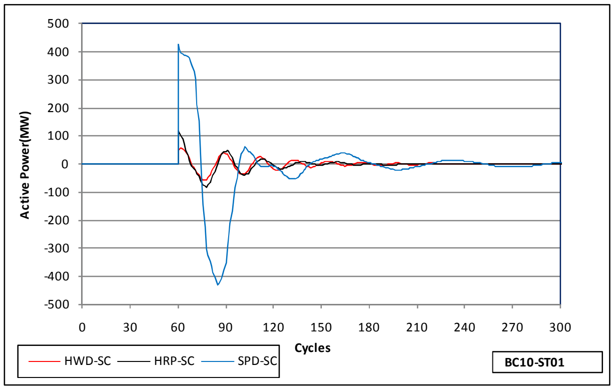
3.3 Summer Day Light Load Conditions

For summer daytime, light load conditions, an Island load of 700 MW was considered. Scenario BC-10 was selected for analysis as this scenario has the highest dc link loadings. The same fault cases were studied as for Scenarios BC-2 and BC-7. The faults were seen to be generally less severe under BC-10 and the general observations made for the previous scenarios apply to these results. The results under BC-10 are presented in the following figures.

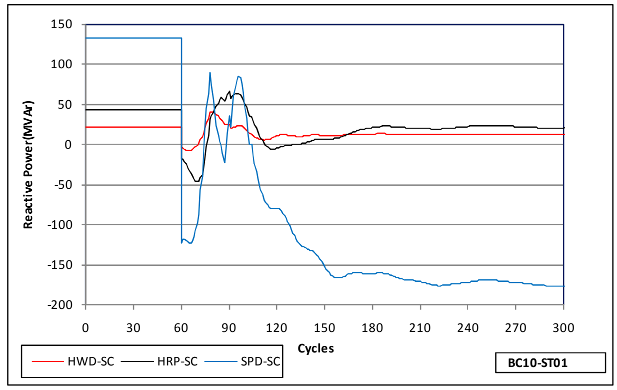
The only item of major significance from these studies is that the temporary over-voltages seen at Bottom Brook when the Maritime Link is blocked and the fault removed were higher than in the previous scenarios, reaching a maximum value of 170% for a fault at Bottom Brook 230 kV on the line to Granite Canal (Figure 3-30). As before, this temporary over-voltage lasts for only a few cycles and is within the temporary over-voltage capability of zinc oxide arresters (180% of maximum system voltage for 0.1 s) and the substation equipment.

Figure 3-25: BC10-ST01, Light/Island Link 900 MW/Maritime Link 500 MW Temporary Bipole Fault on Island Link

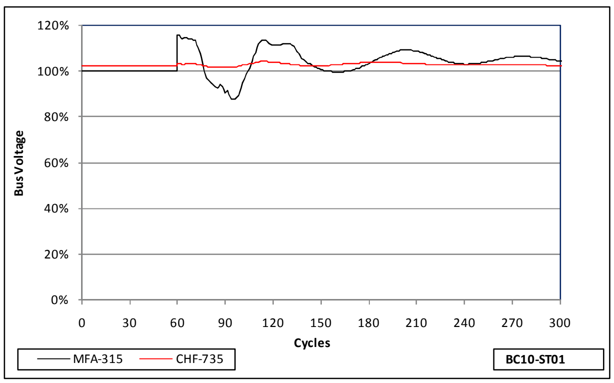




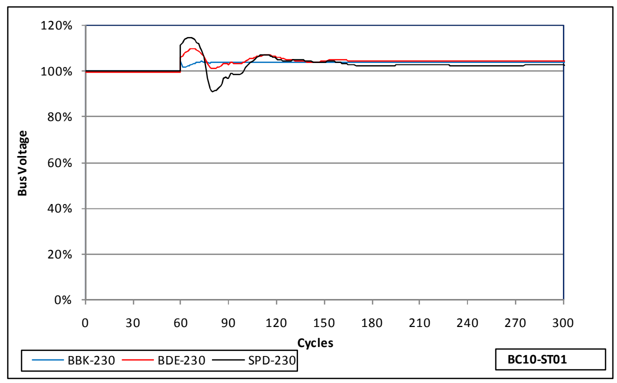
Active Power(MW)
500
400
300
200
100
0
-100
-200
-300
-400
-500
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST01



Reactive Power(MVAr)
150
100
50
0
-50
-100
-150
-200
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST01



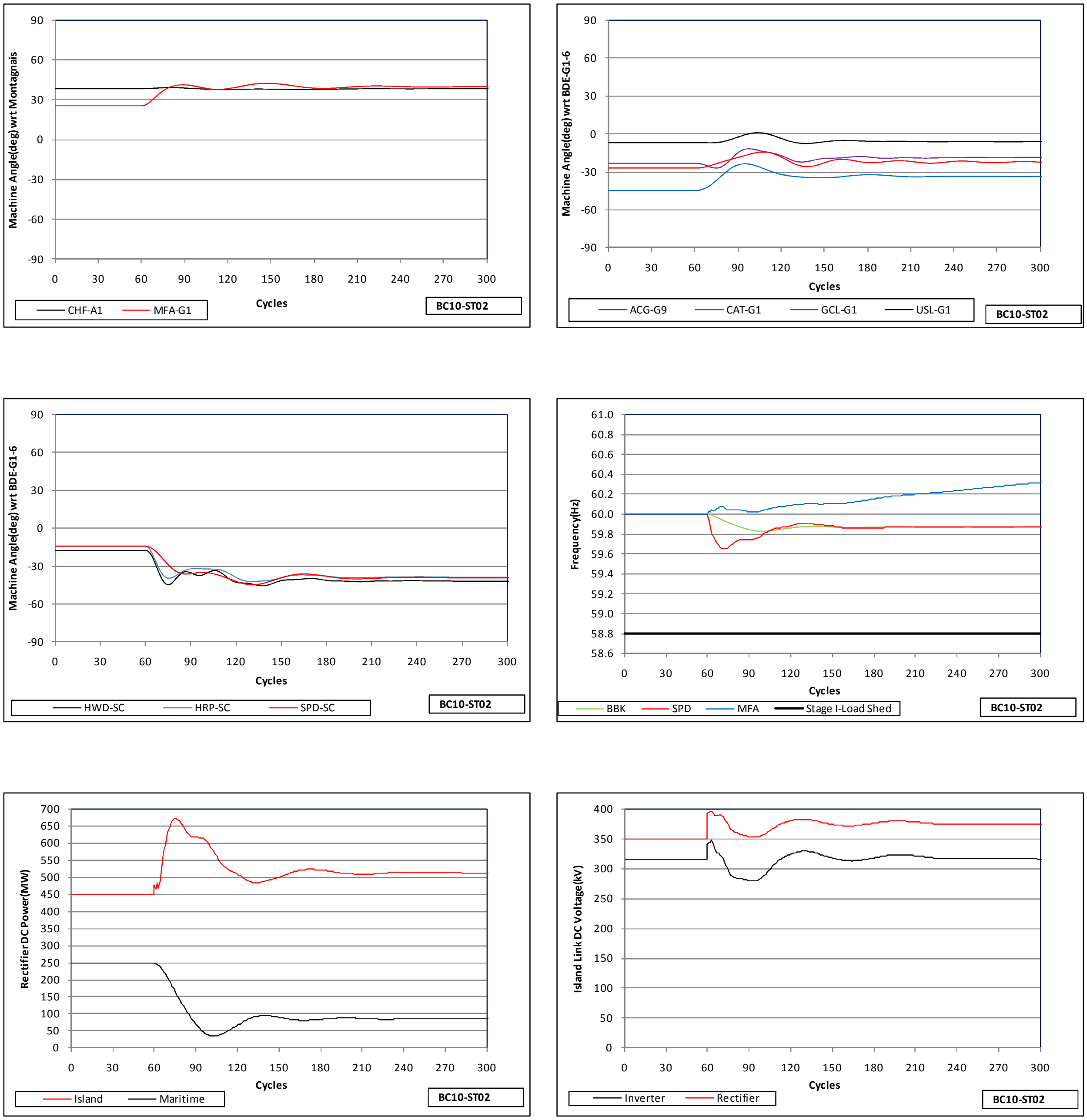
Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
MFA-315
CHF-735
BC10-ST01



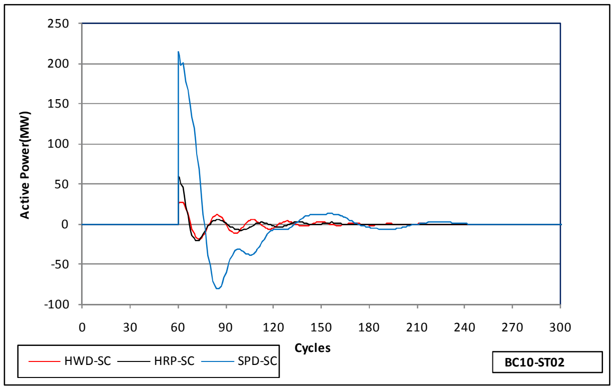
Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
BBK-230
BDE-230
SPD-230
BC10-ST01

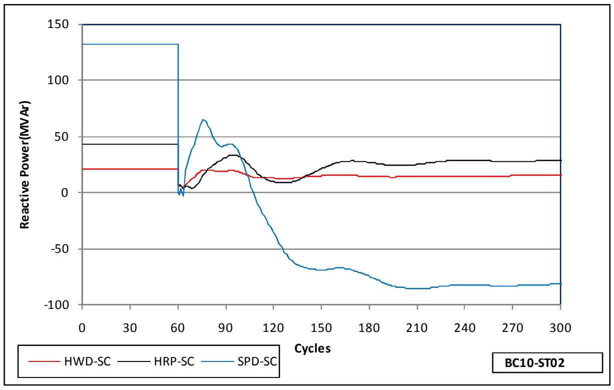
SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	82

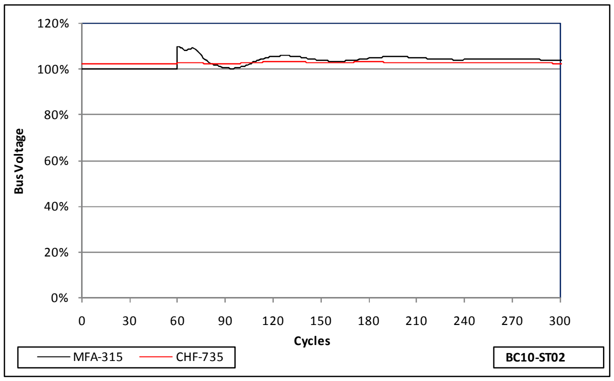
Figure 3-26: BC10-ST02, Light/Island Link 900 MW/Maritime Link 500 MW Permanent Pole Outage on Island Link

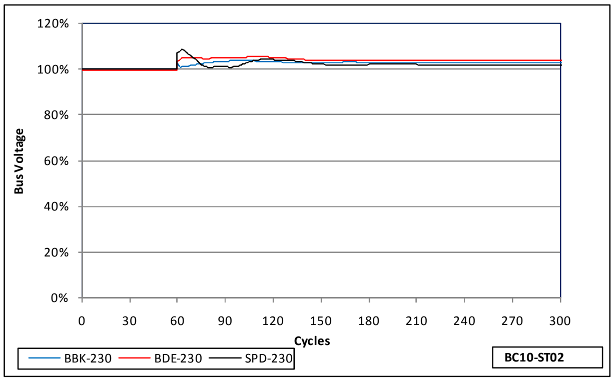


SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	83



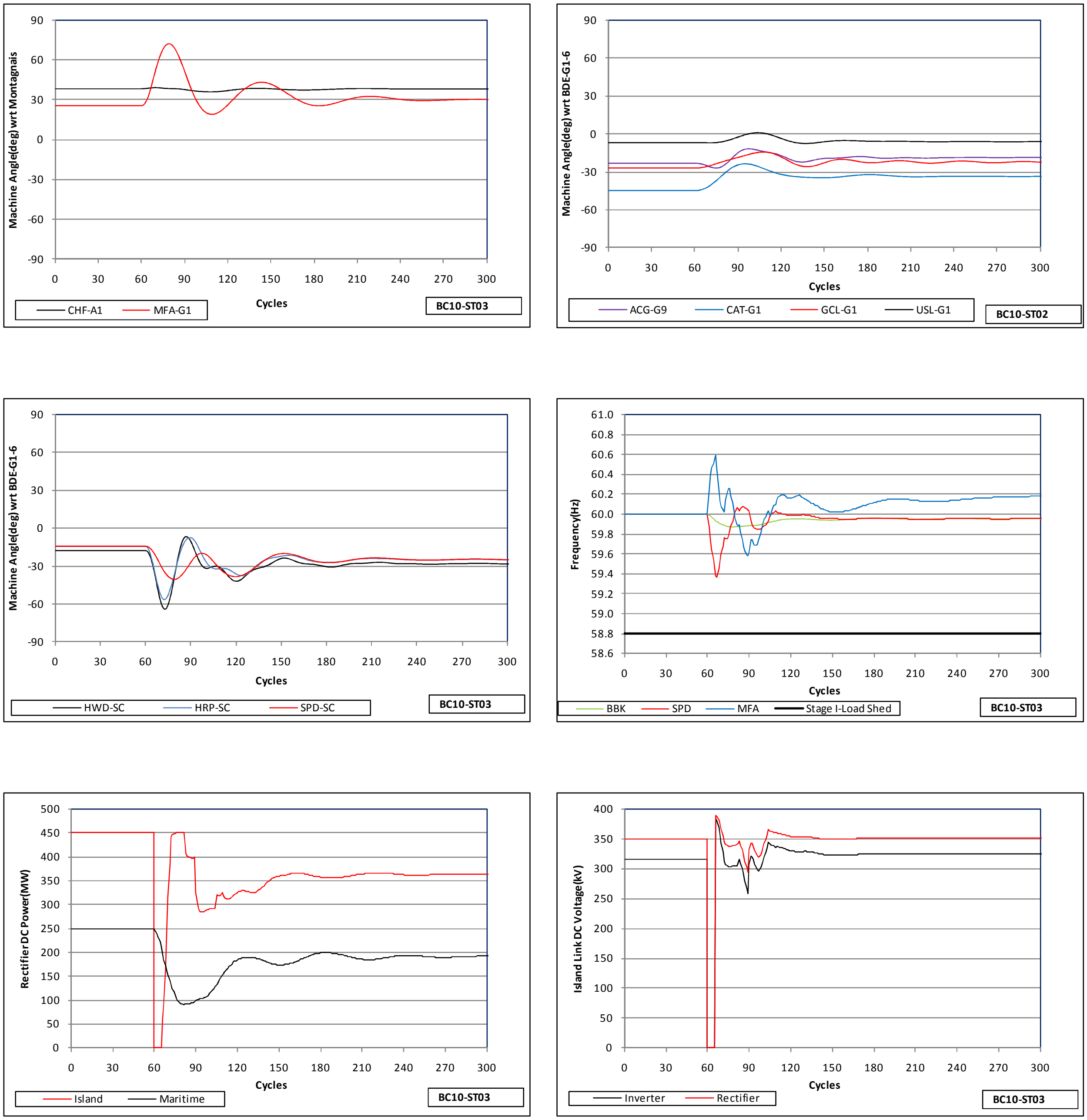


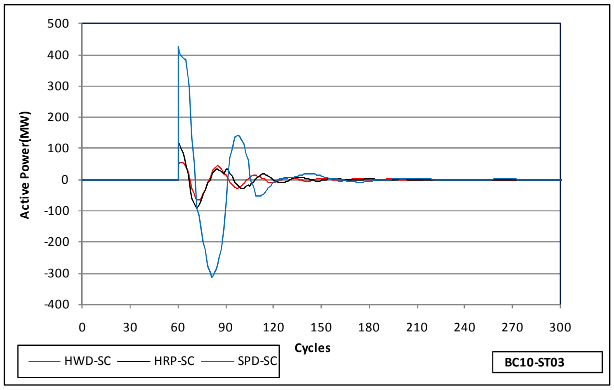


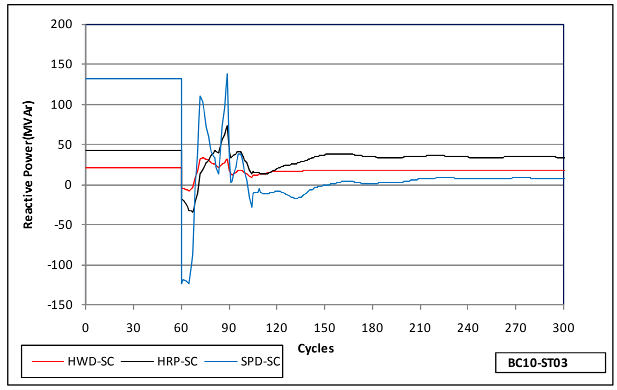


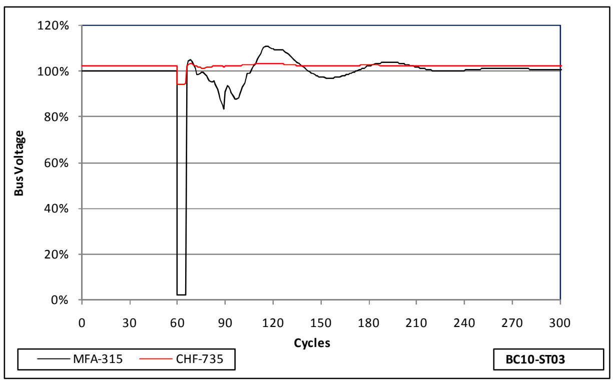
SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	84

Figure 3-27: BC10-ST03, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Muskrat Falls 315 kV on line to Churchill Falls




Active Power(MW)
500
400
300
200
100
0
-100
-200
-300
-400
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST03


Reactive Power(MVAr)
200
150
100
50
0
-50
-100
-150
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST03


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
MFA-315
CHF-735
BC10-ST03

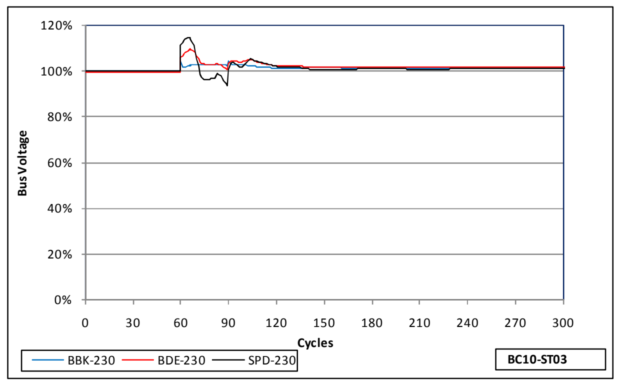
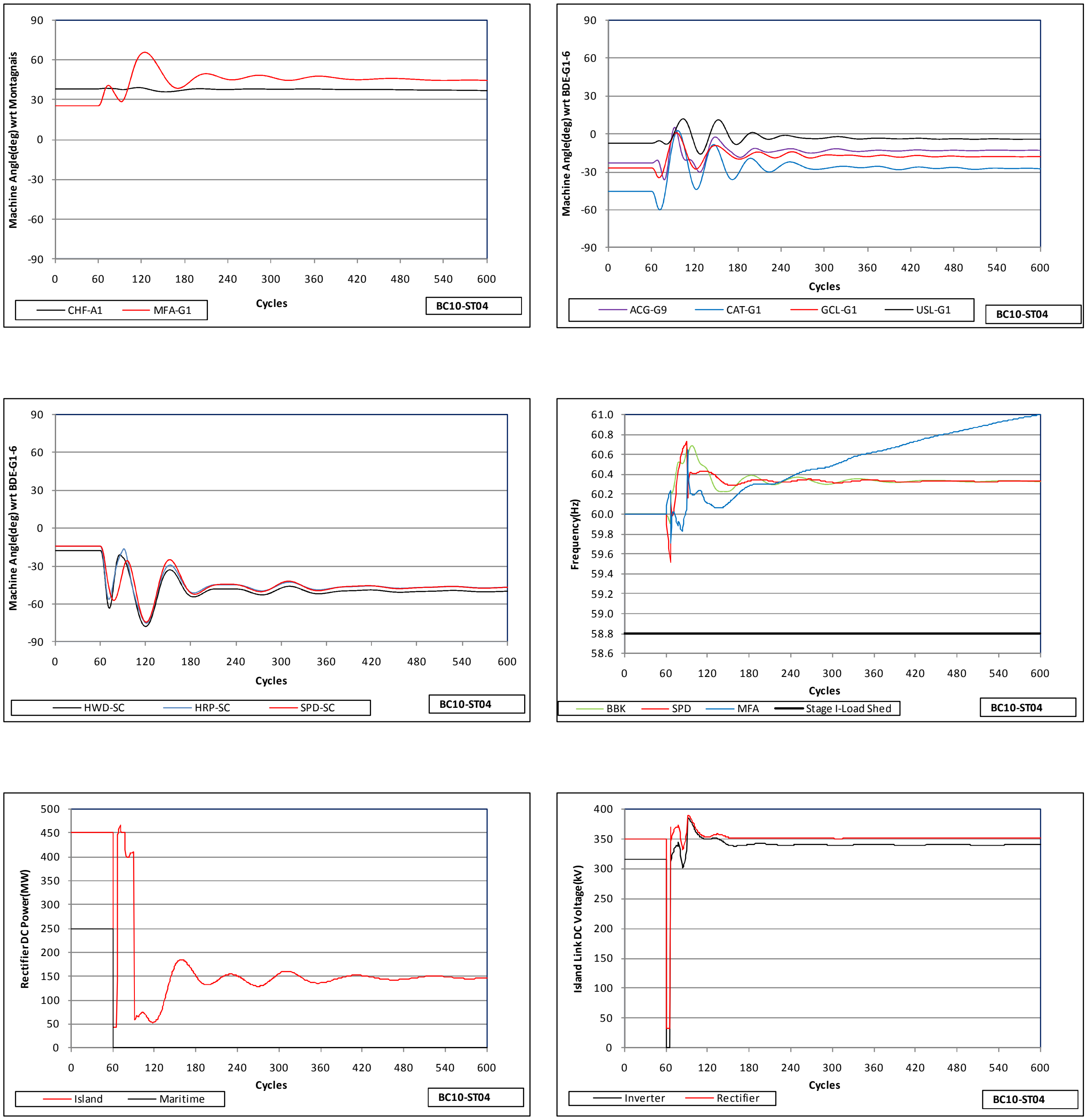
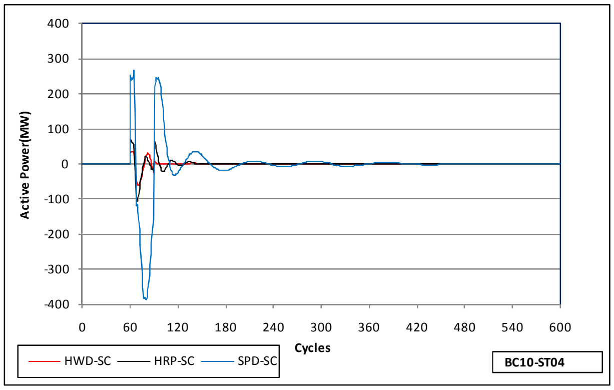
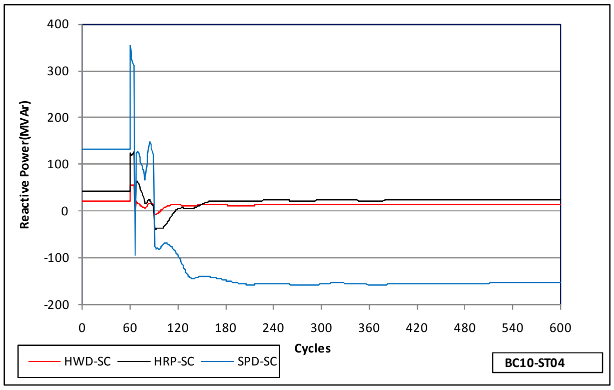
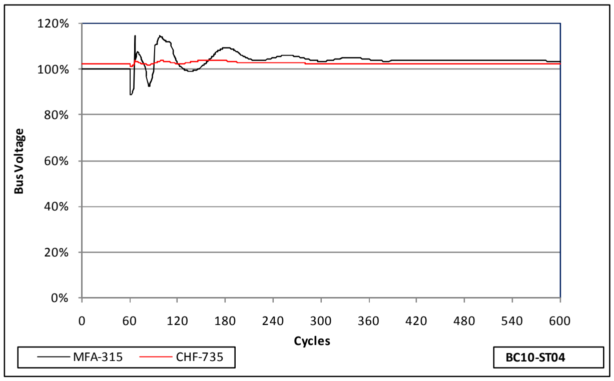

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
BBK-230
BDE-230
SPD-230
BC10-ST03

Figure 3-28: BC10-ST04, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Bay d'Espoir 230 kV on line to Western Avalon




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST04


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST04


Bus Voltage
Cycles
MFA-315
CHF-735
BC10-ST04

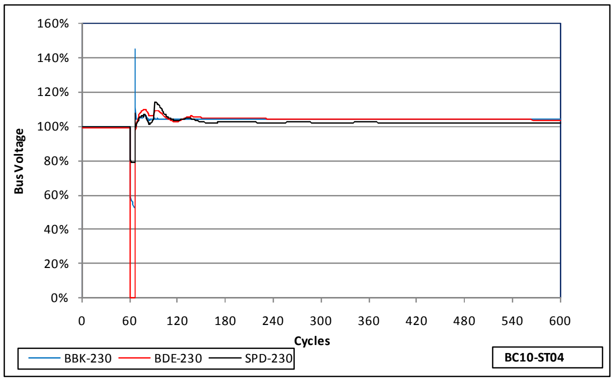
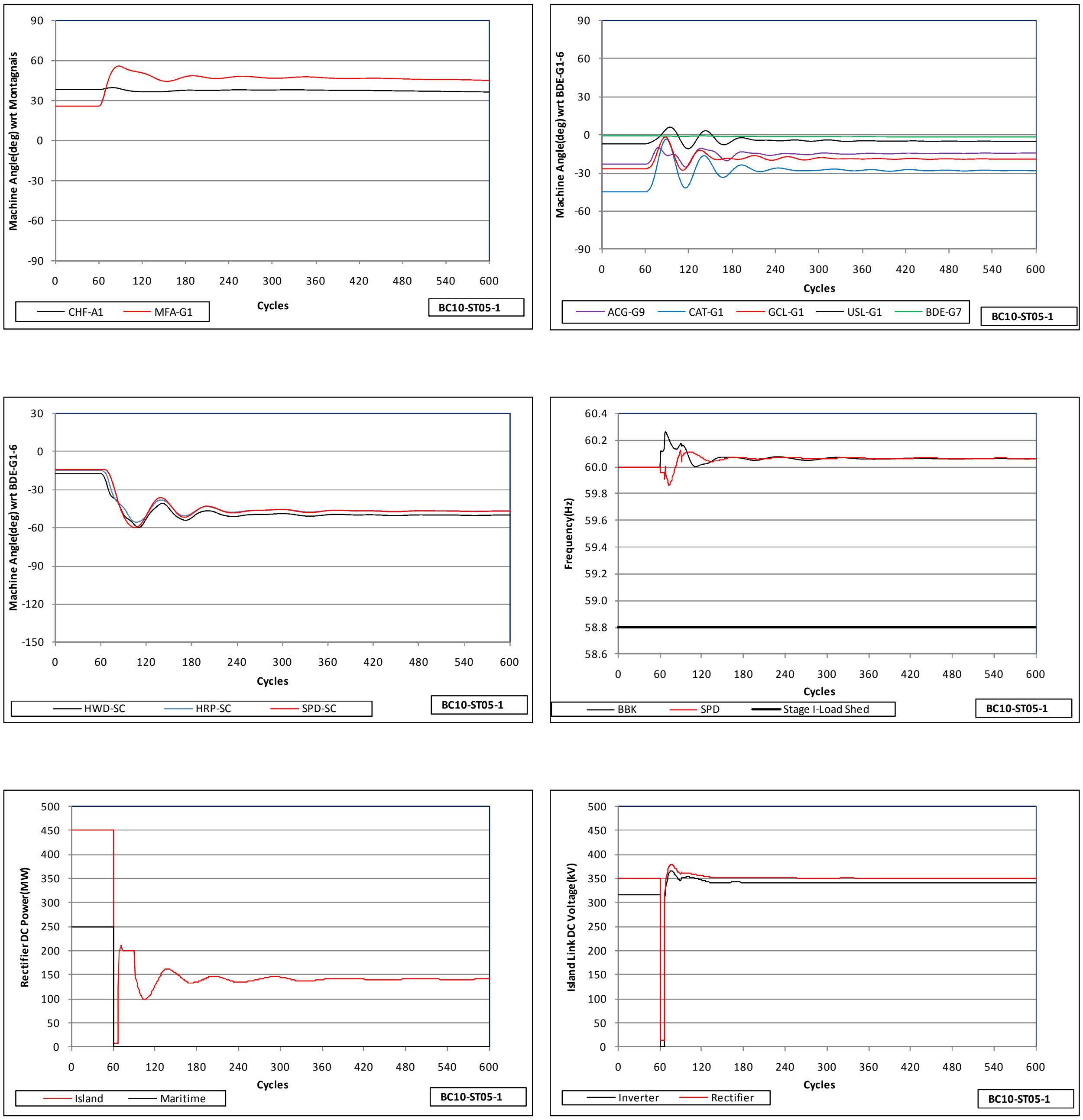
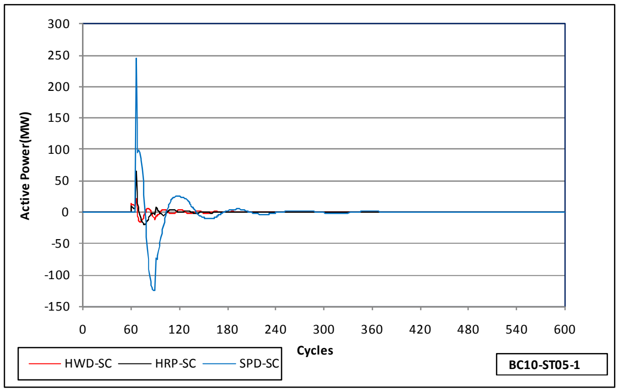
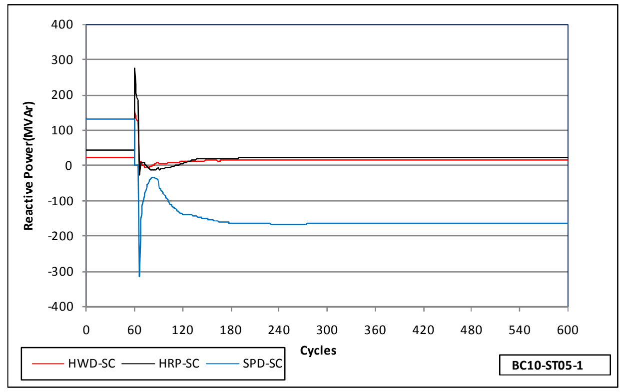

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC10-ST04

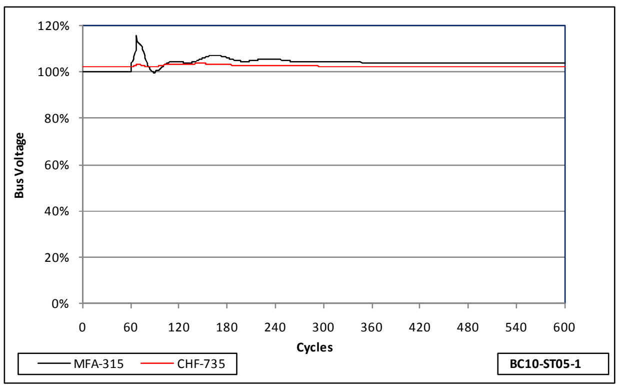
Figure 3-29: BC10-ST05-1, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Soldiers Pond 230 kV on line to Western Avalon (TL217W)



SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	89







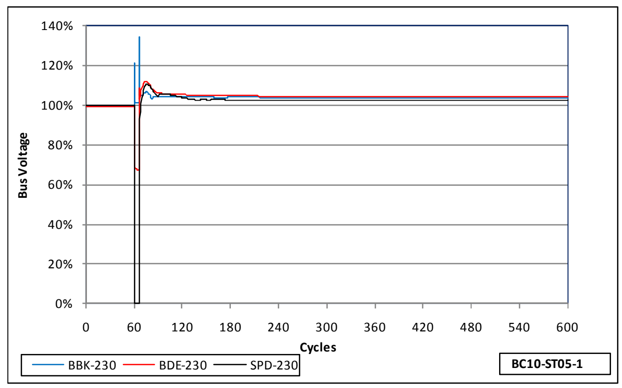
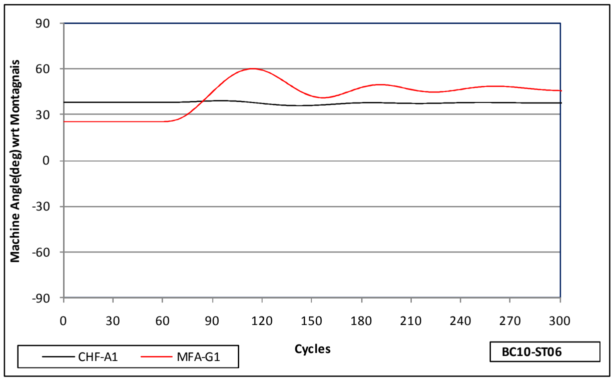
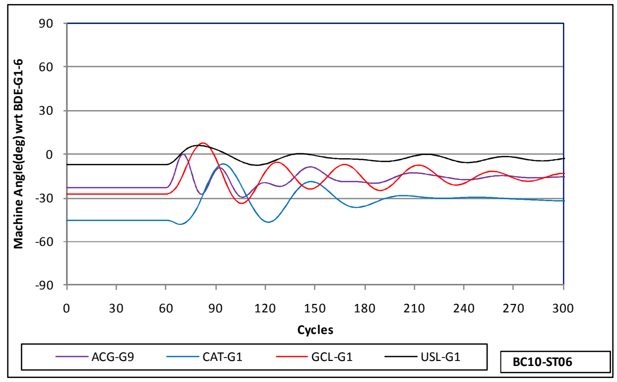
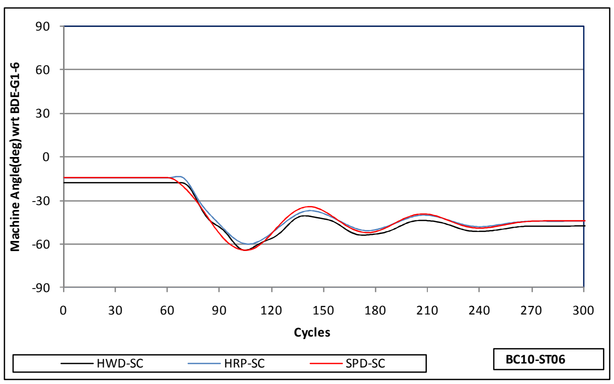
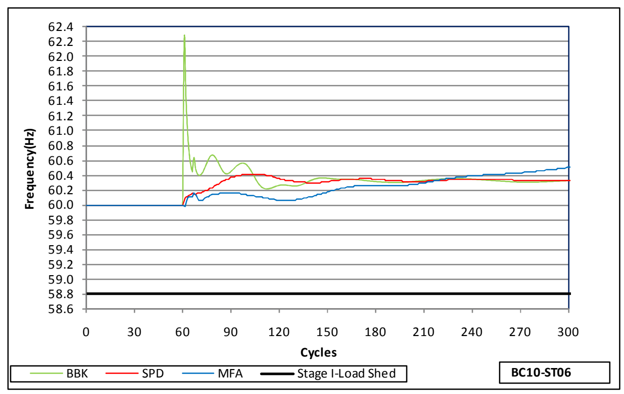


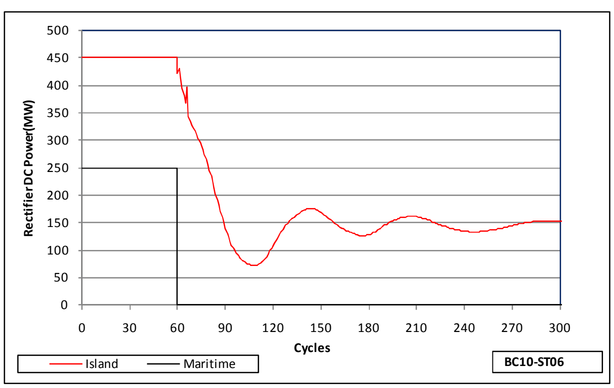
Figure 3-30: BC10-ST06, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Bottom Brook 230 kV on line to Granite Canal

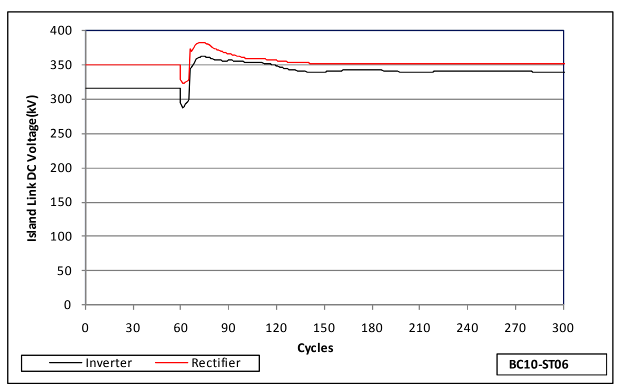




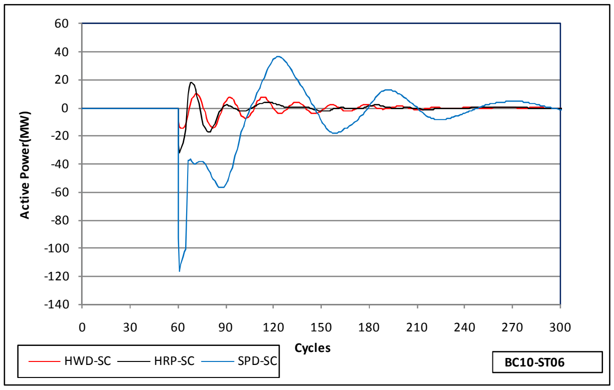


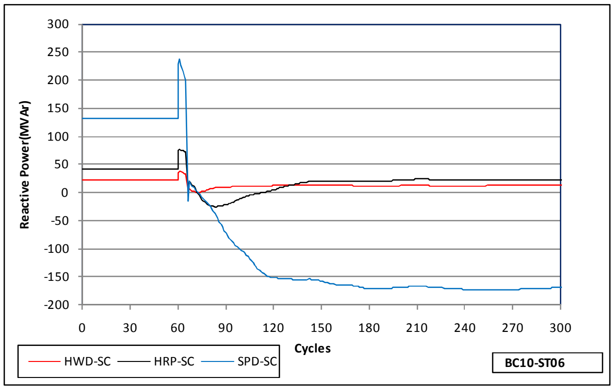


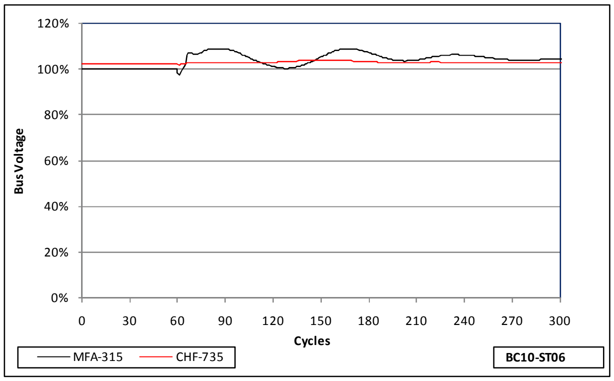




SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	91







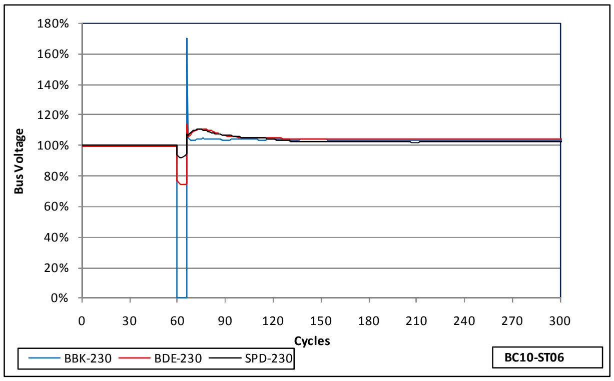
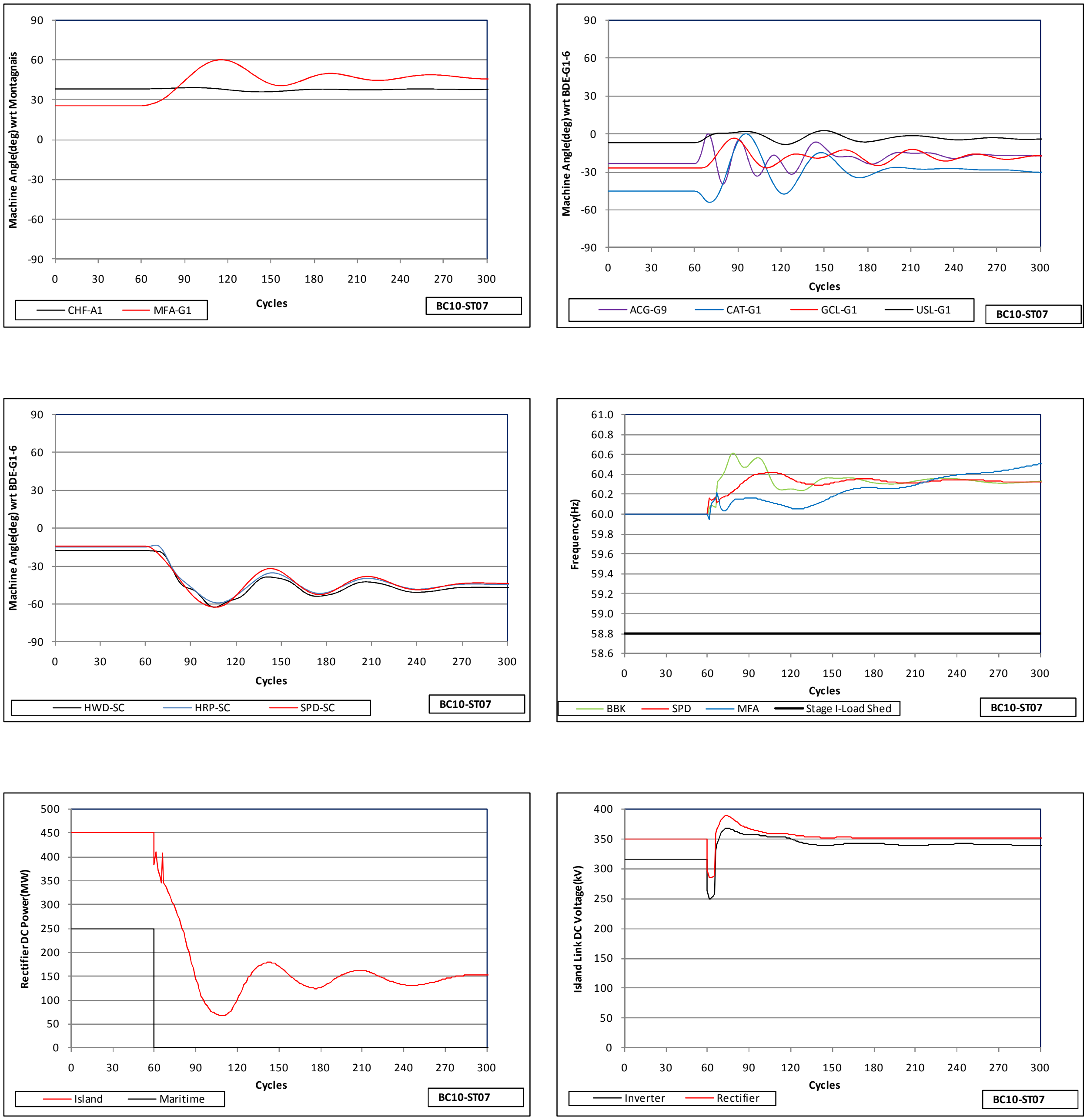
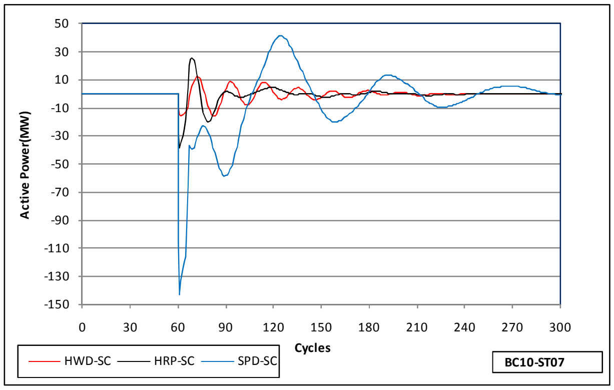
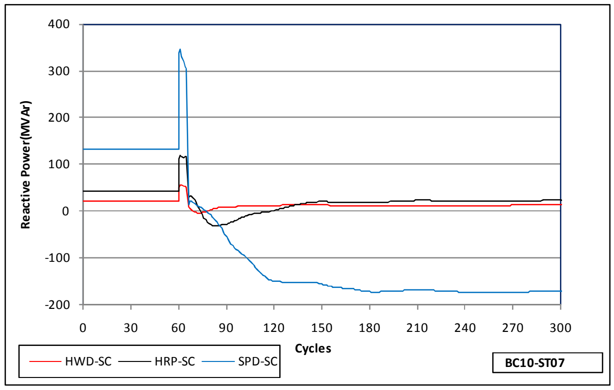
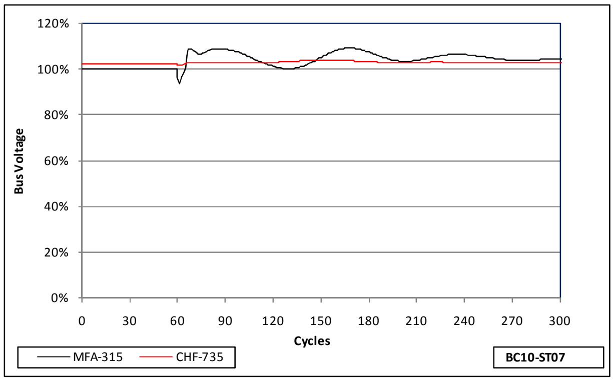


Figure 3-31: BC10-ST07, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Stony Brook 230 kV on line to Bay d'Espoir (TL204)




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST07


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST07


Bus Voltage
Cycles
MFA-315
CHF-735
BC10-ST07

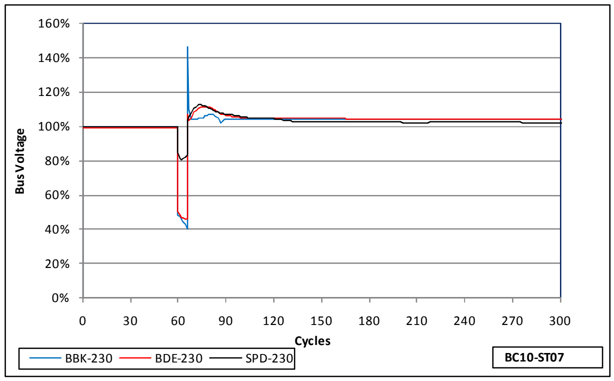
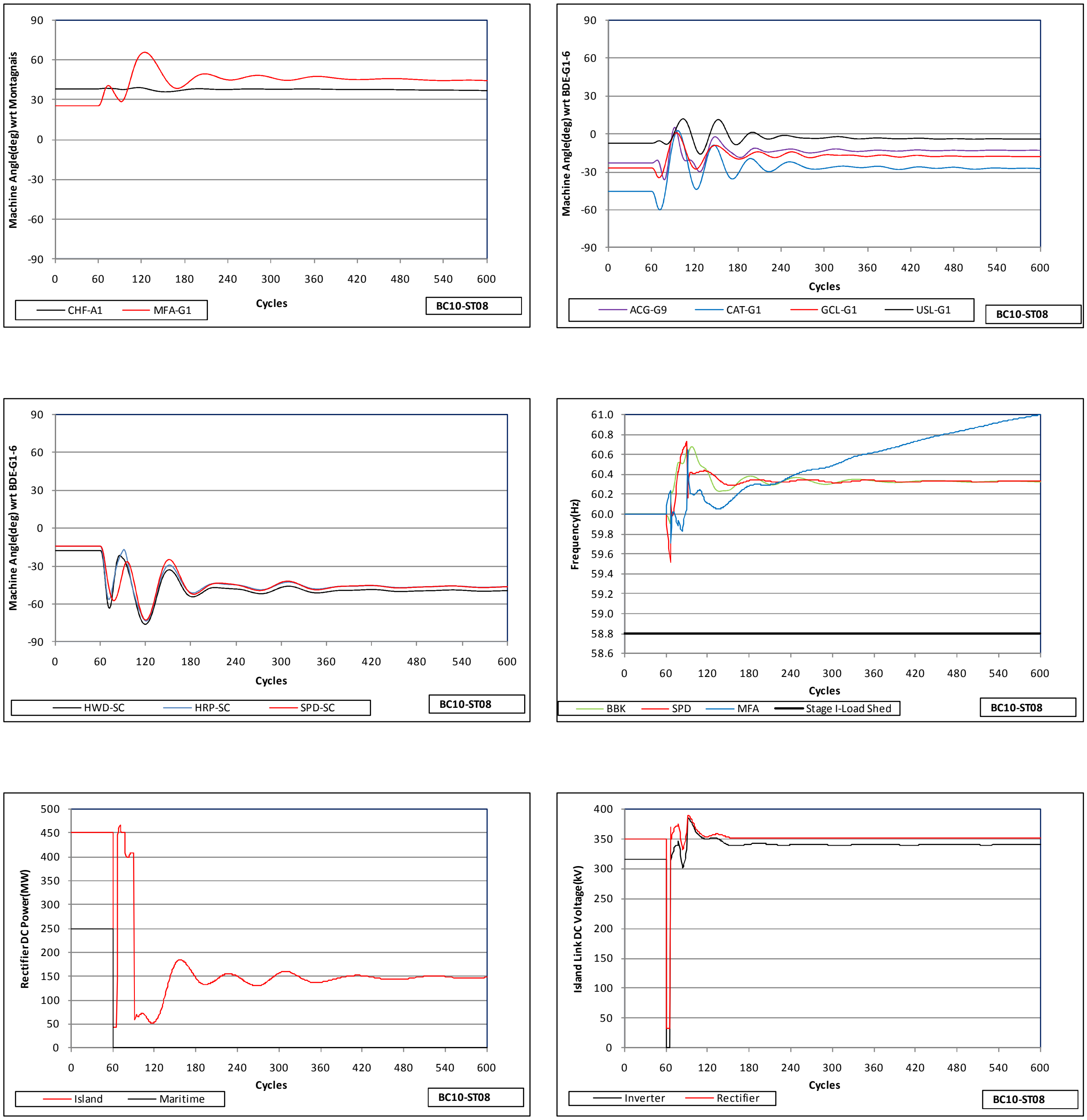
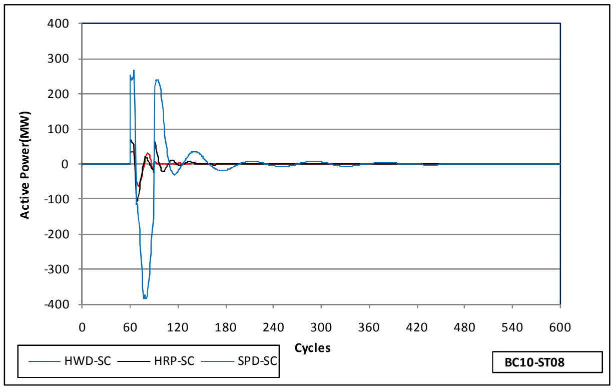
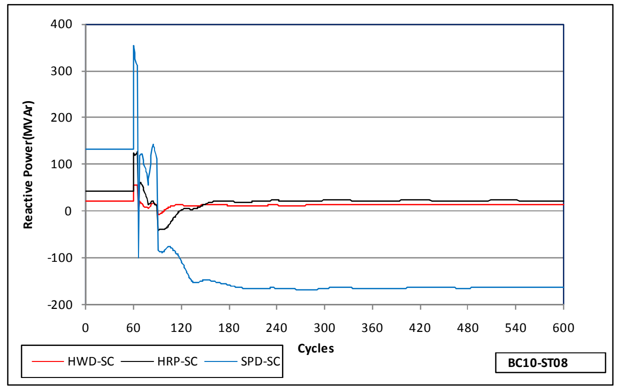

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC10-ST07

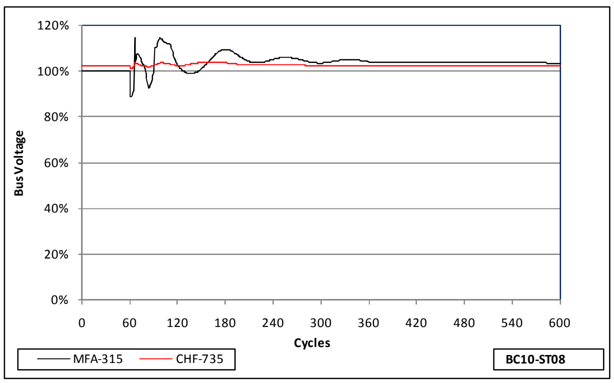
Figure 3-32: BC10-ST08, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Bay d'Espoir 230 kV on line to Sunnyside (TL202)



SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	95







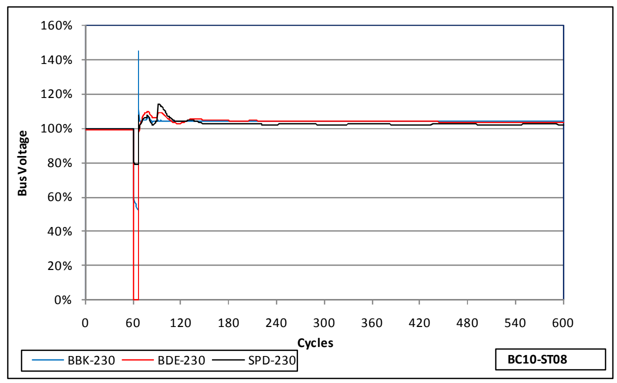
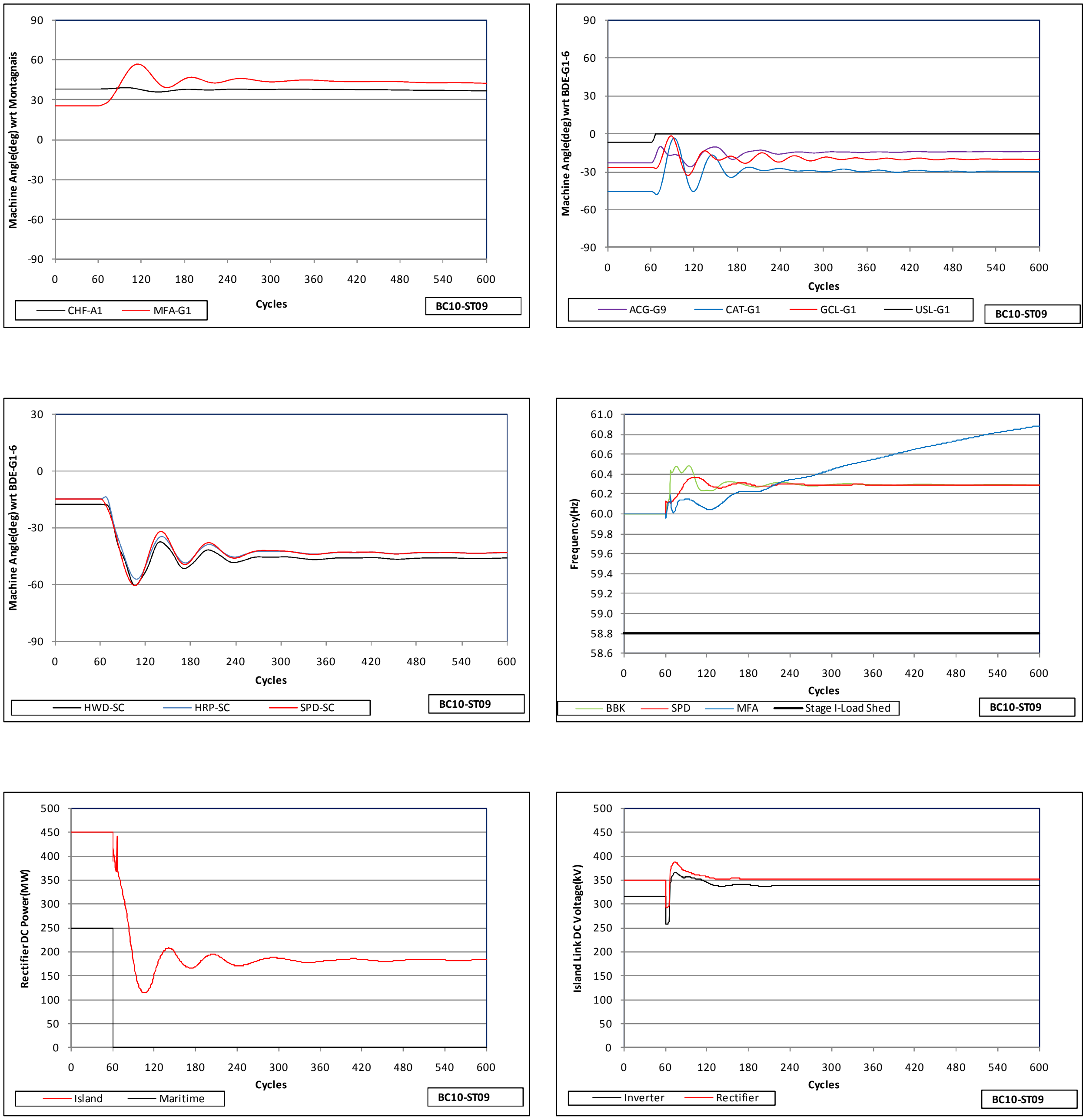
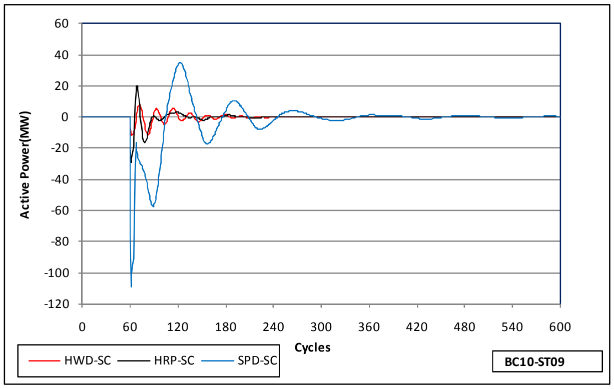
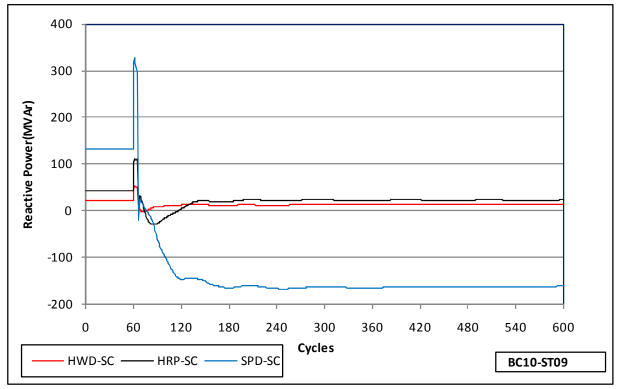
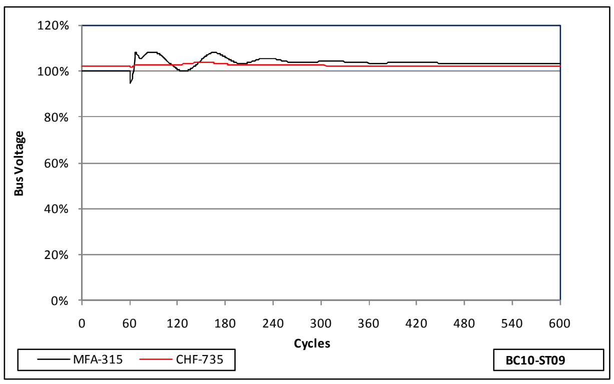


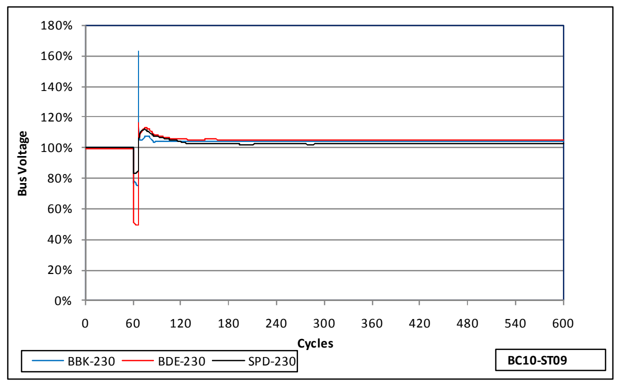
Figure 3-33: BC10-ST09, Light/Island Link 900 MW/Maritime Link 500 MW 6-cycle/3-phase Fault at Upper Salmon 230 kV-Generator Outage G1




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST09


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC10-ST09


Bus Voltage
Cycles
MFA-315
CHF-735
BC10-ST09

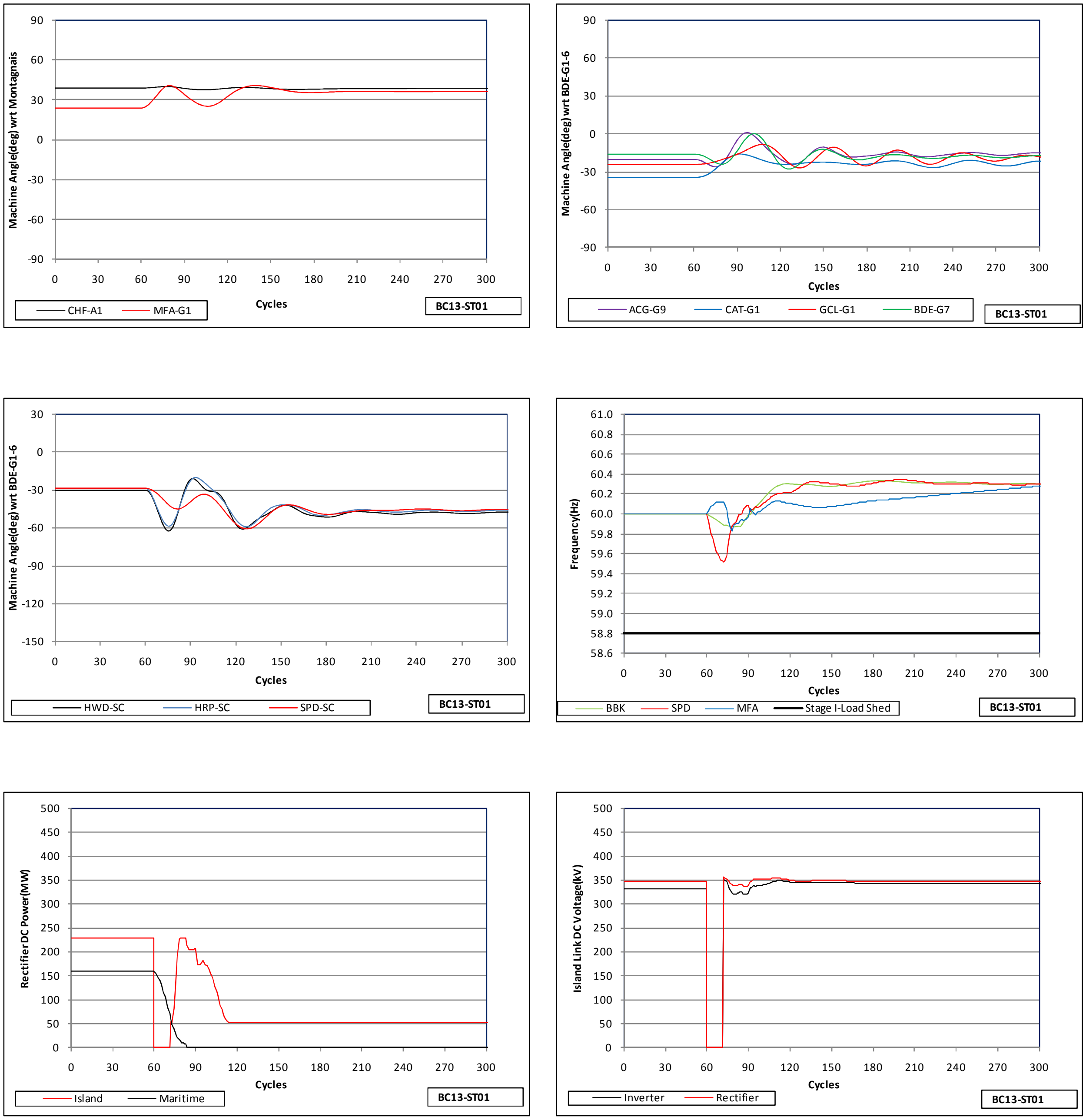

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC10-ST09

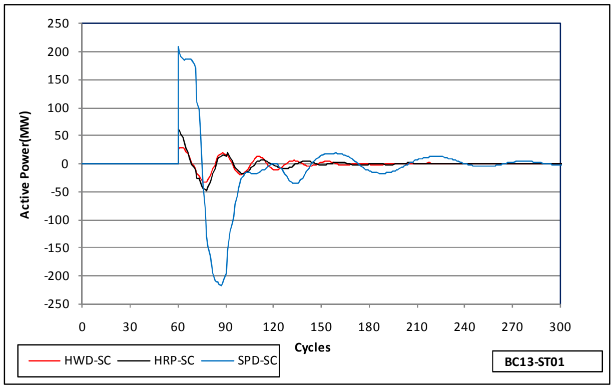
3.4 Summer Night Extreme Light Load Conditions

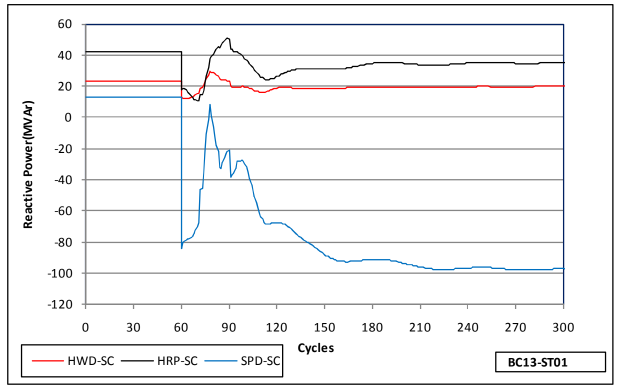
For summer night-time, extreme light load conditions, an Island load of 420 MW was considered. Scenario BC-13 was selected for analysis as this scenario has the highest dc link loadings. The same fault cases were studied as for Scenarios BC-2, BC-7 and BC-10. The faults were seen to be generally less severe under BC-13 and the general observations made for the previous scenarios apply to these results. The results under Scenario BC-13 are presented in the following figures.

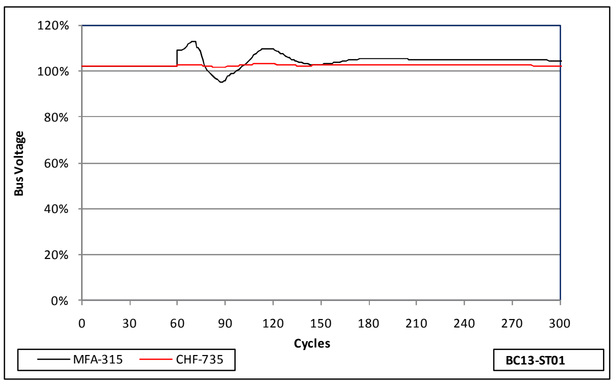
The only item of major significance from these studies is that the temporary over-voltages seen at Bottom Brook when the Maritime Link is blocked and the fault removed were higher than in the previous scenarios, reaching a maximum value of 180% for a fault at Bottom Brook 230 kV on the line to Granite Canal (Figure 3-39). As before, this temporary over-voltage lasts for only a few cycles and is within the temporary over-voltage capability of zinc oxide arresters (180% for 0.1 s) and the substation equipment.

Figure 3-34: BC13-ST01, Extreme Light/Island Link 435 MW/Maritime Link 320 MW Temporary Bipole Fault on Island Link




Active Power(MW)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST01


Reactive Power(MVAr)
60
40
20
0
-20
-40
-60
-80
-100
-120
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST01


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
MFA-315
CHF-735
BC13-ST01

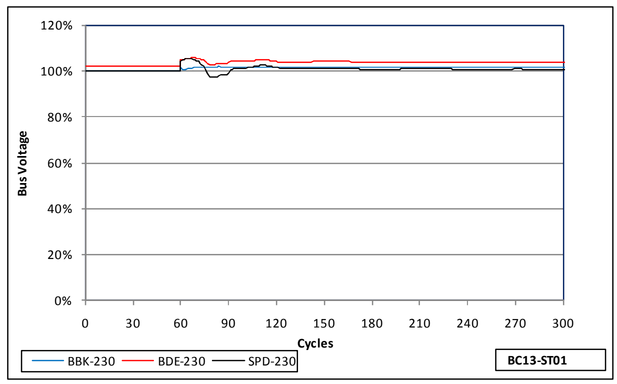
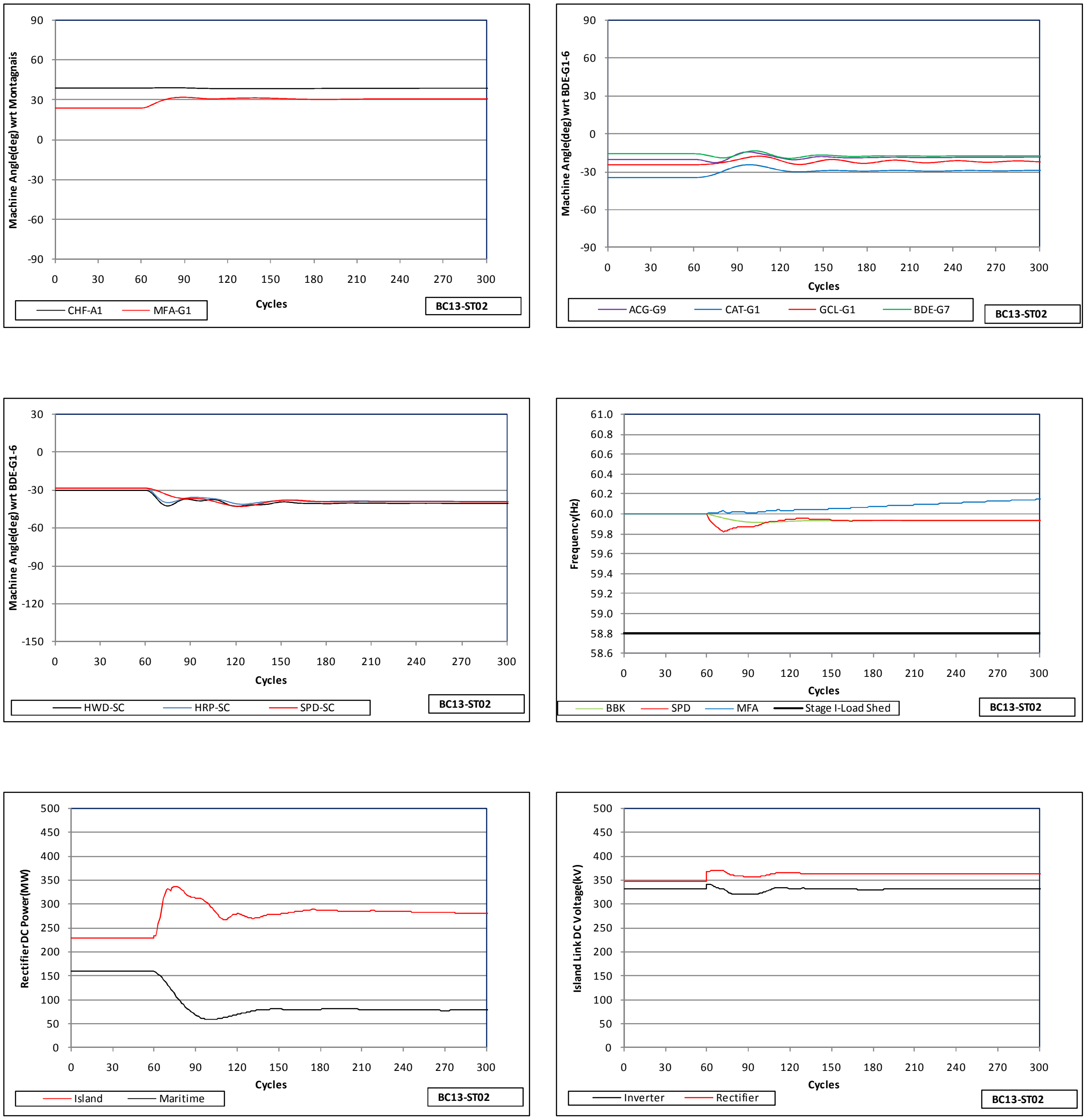
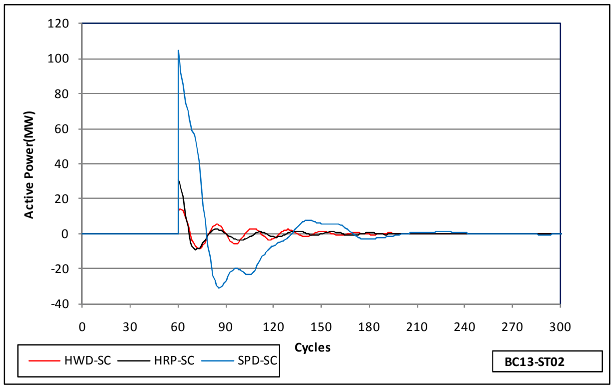
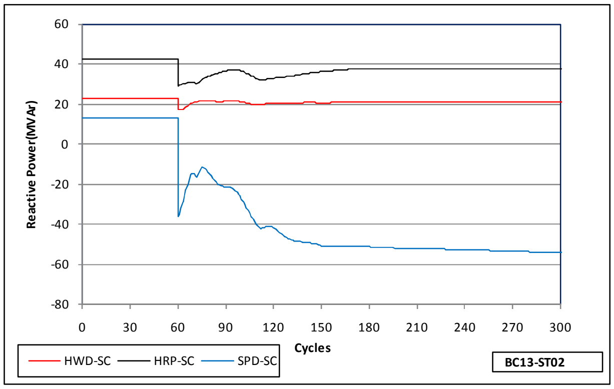
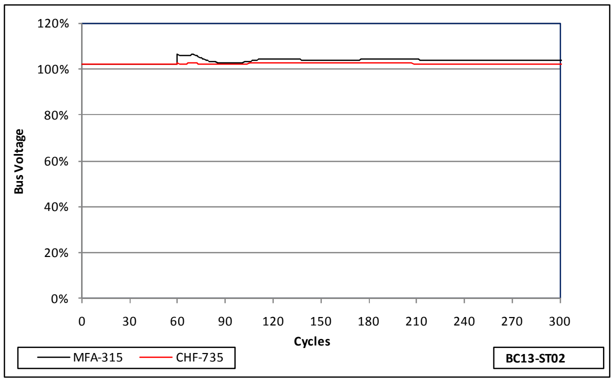

Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST01

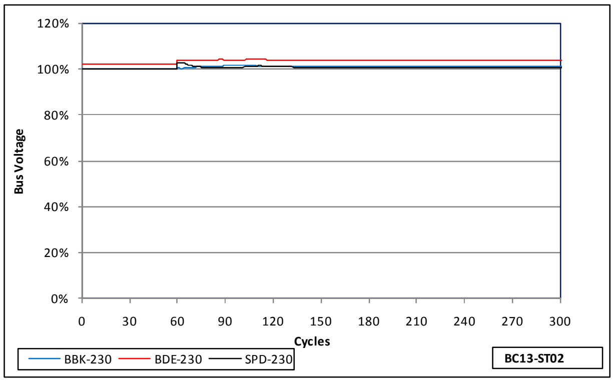
Figure 3-35: BC13-ST02, Extreme Light/Island Link 435 MW/Maritime Link 320 MW Permanent Pole Outage on Island Link




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST02

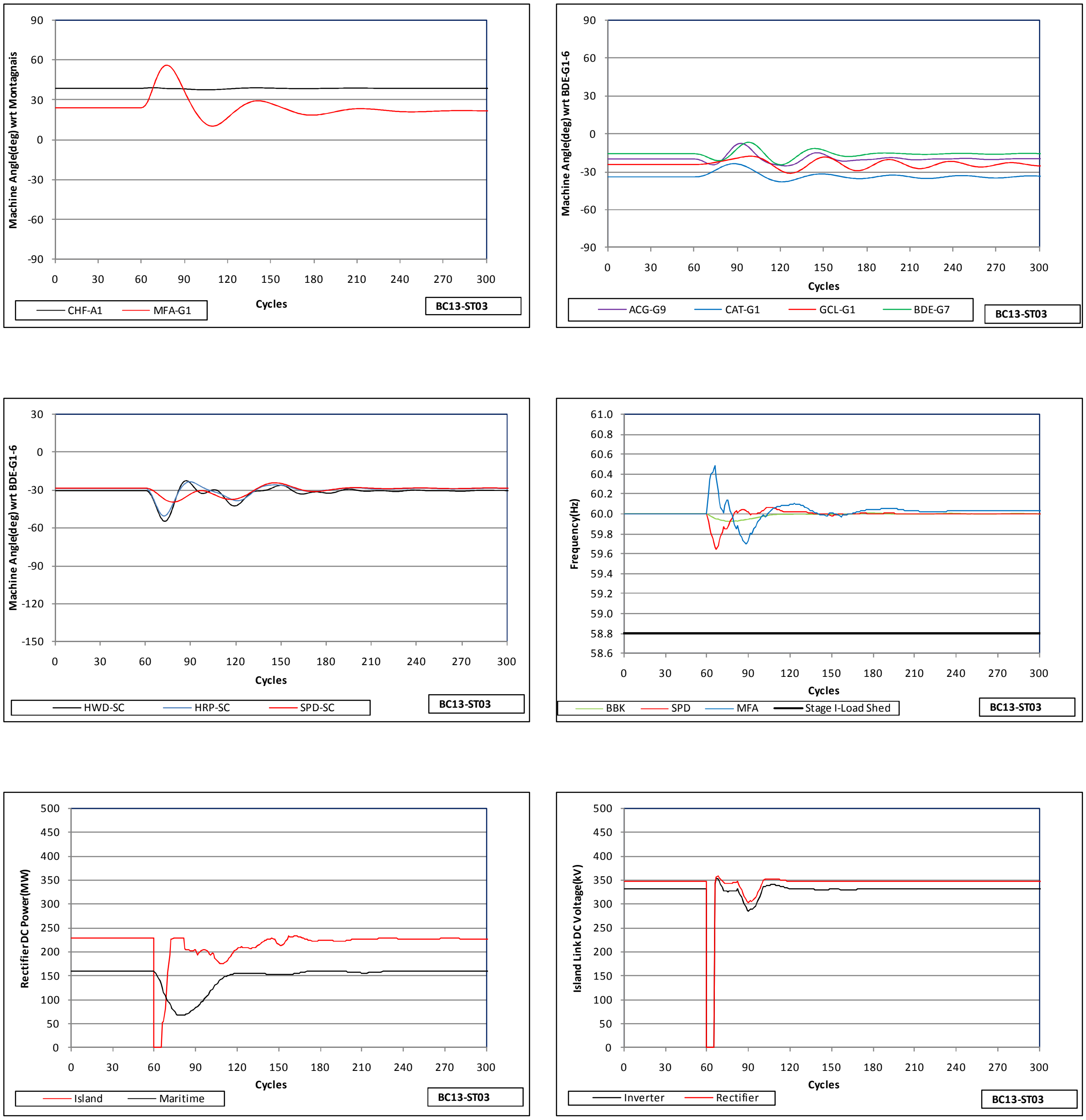

Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST02


Bus Voltage
Cycles
MFA-315
CHF-735
BC13-ST02

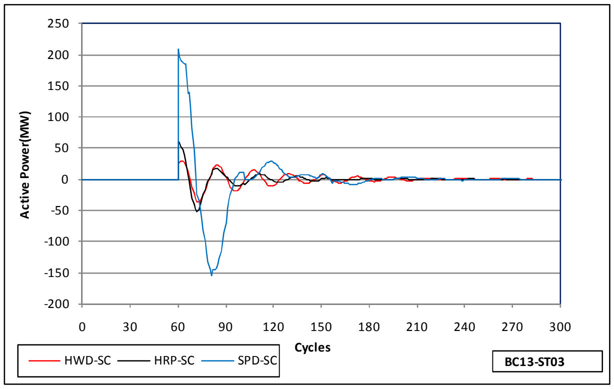

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST02

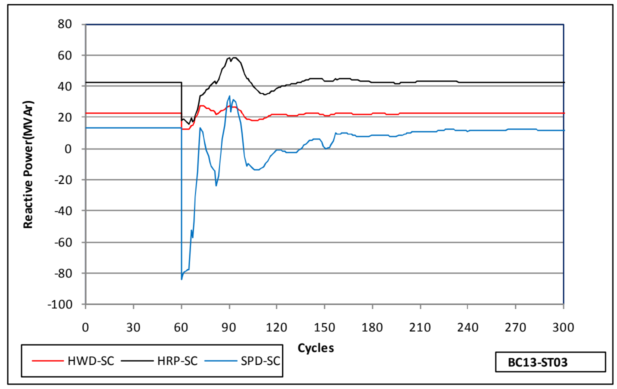
SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	103

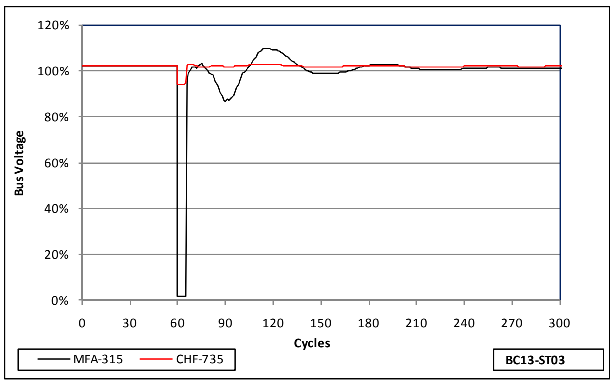
Figure 3-36: BC13-ST03, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Muskrat Falls 315 kV on line to Churchill Falls



SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	104







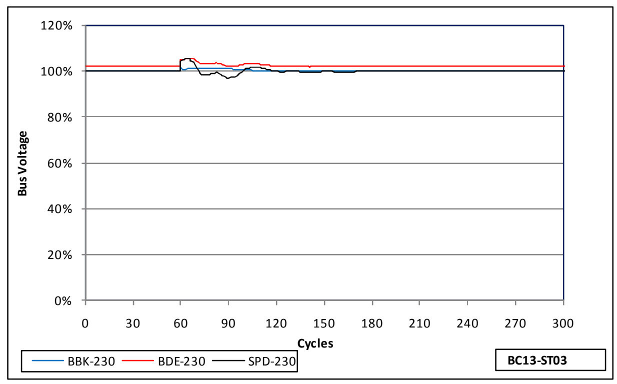
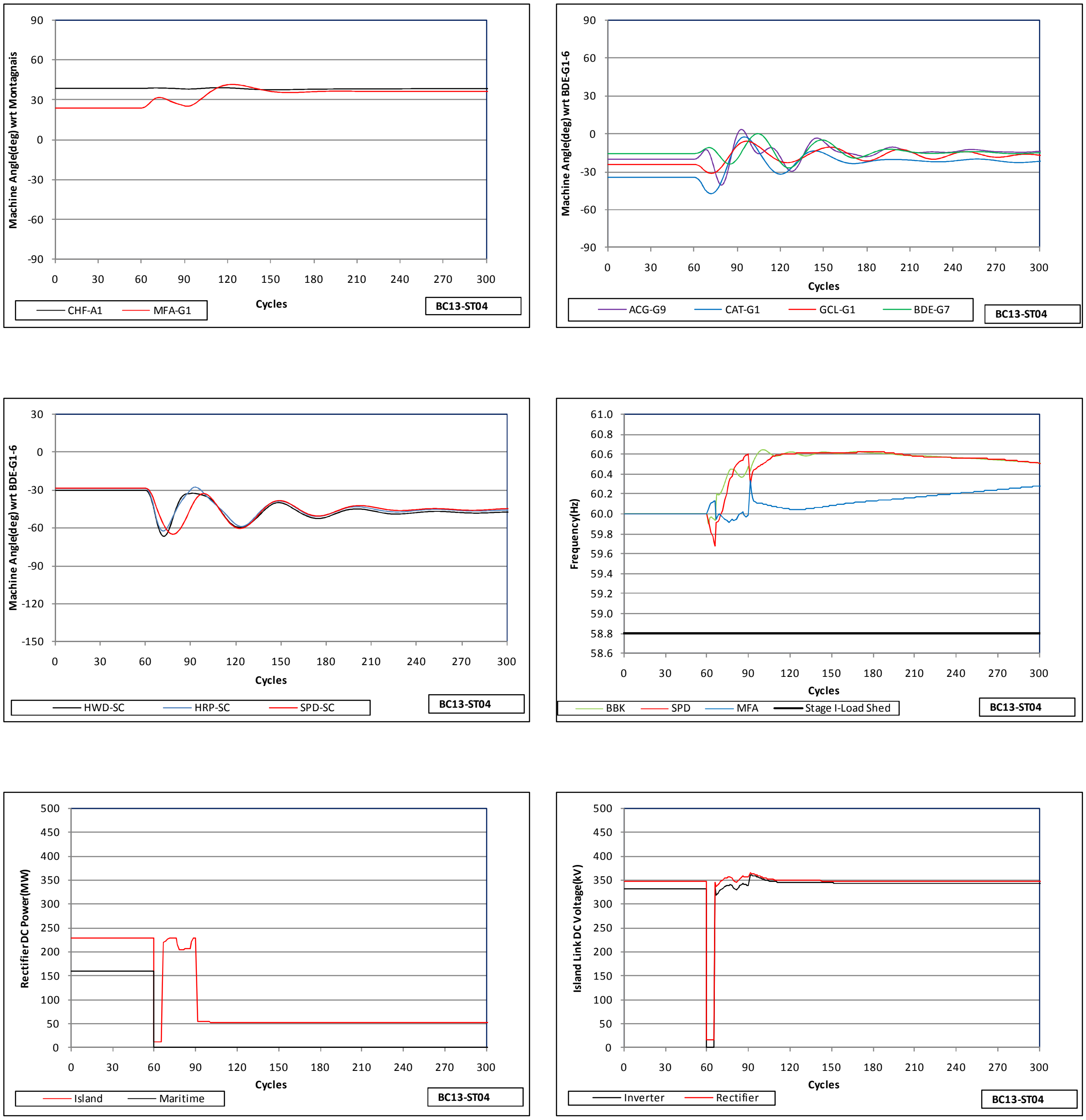
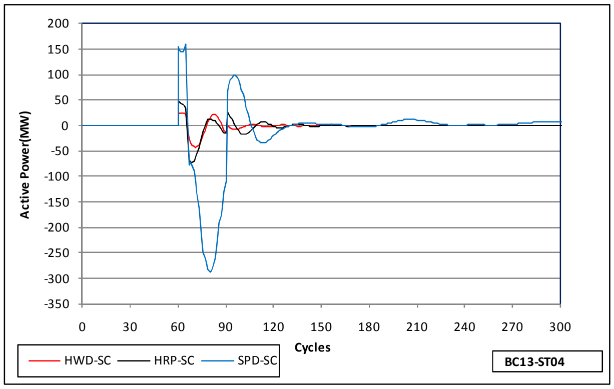
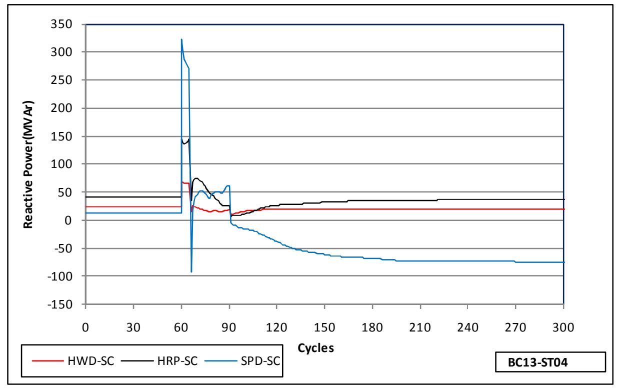
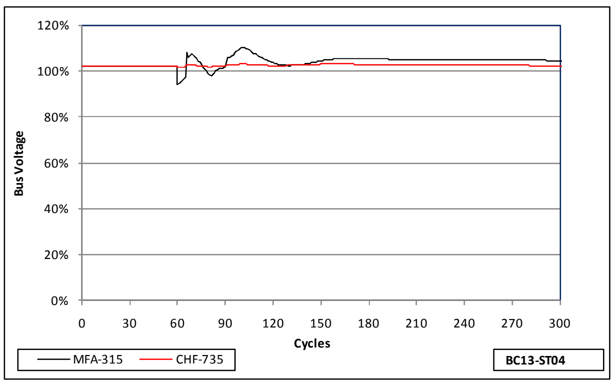


Figure 3-37: BC13-ST04, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Bay d'Espoir 230 kV on line to Western Avalon




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST04


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST04


Bus Voltage
Cycles
MFA-315
CHF-735
BC13-ST04

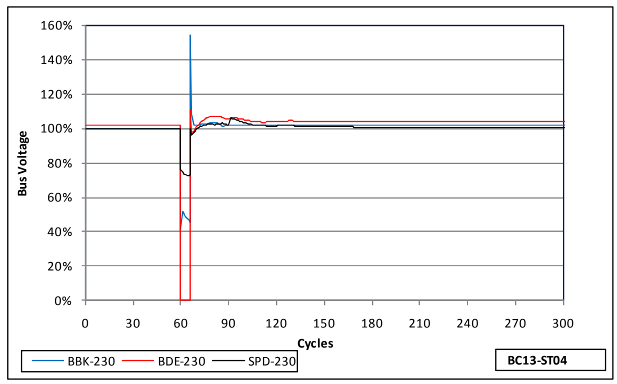
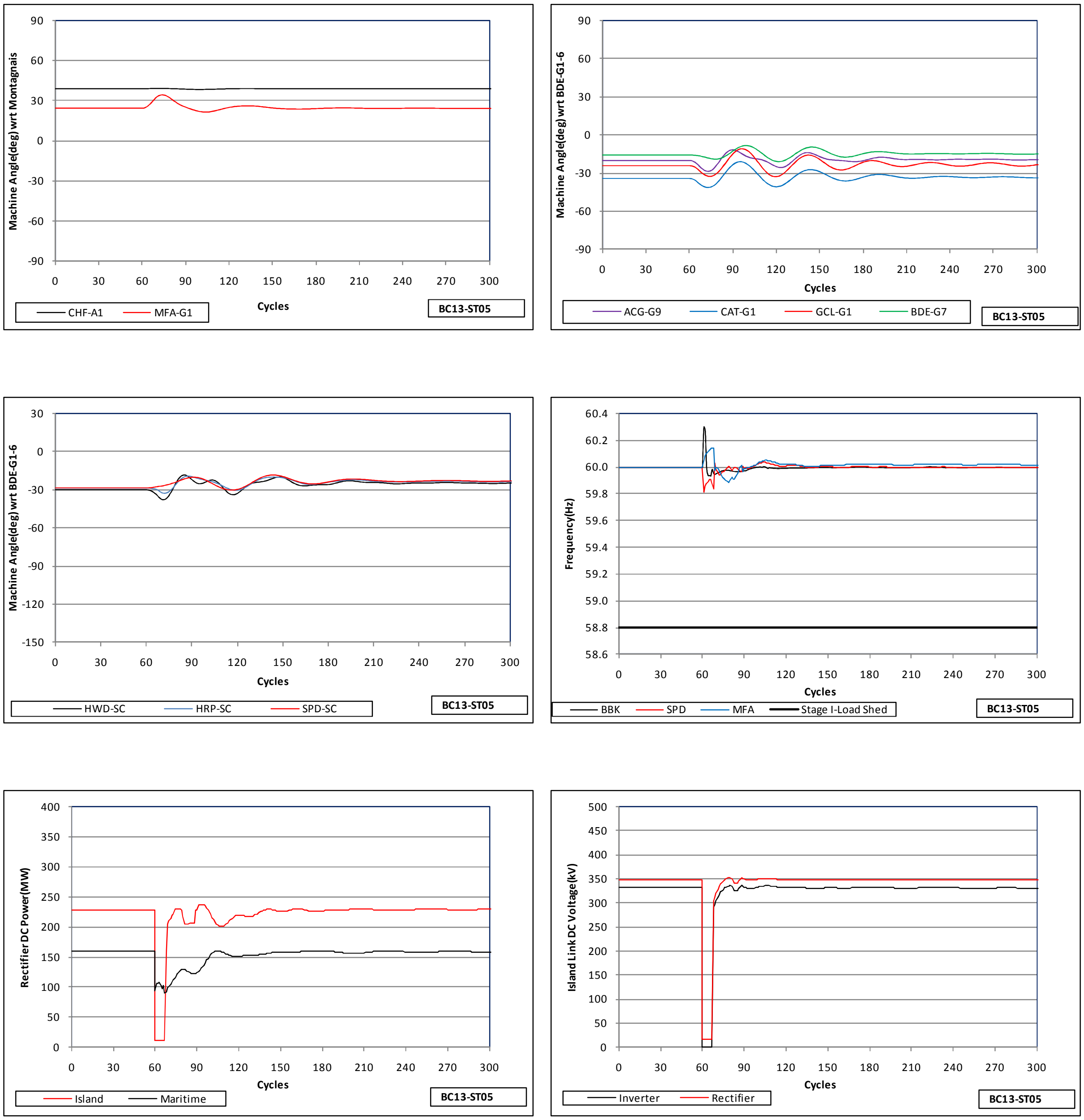
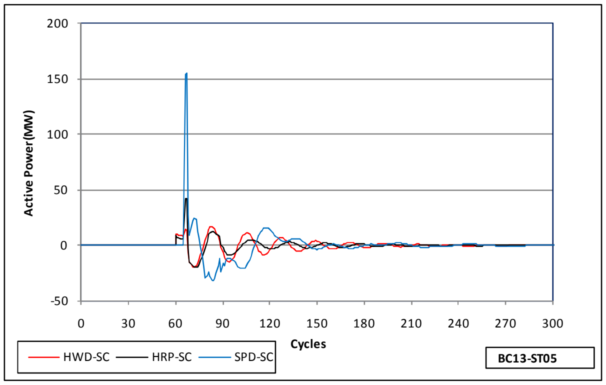
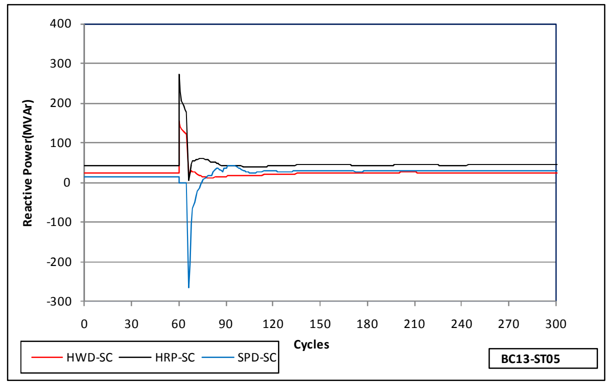
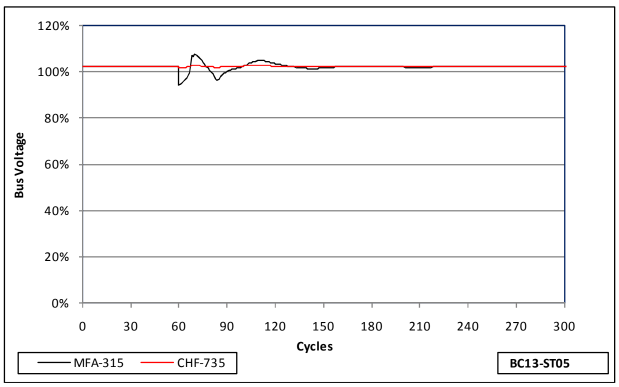

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST04

Figure 3-38: BC13-ST05, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Soldiers Pond 230 kV on line to Western Avalon (TL217W)




Active Power(MW)
200
150
100
50
0
-50
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST05


Reactive Power(MVAr)
400
300
200
100
0
-100
-200
-300
0 30 60 90 120 150 180 210 240 270 300
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST05


Bus Voltage
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
MFA-315
CHF-735
BC13-ST05

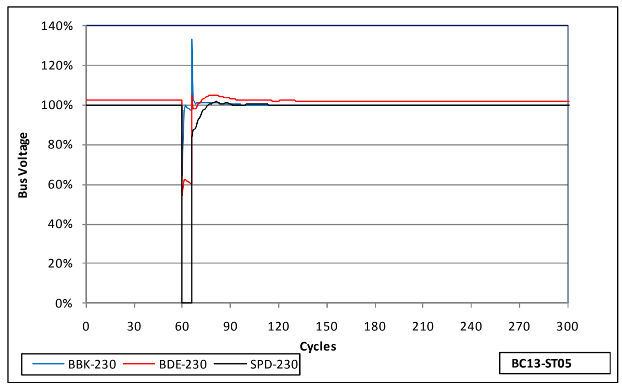
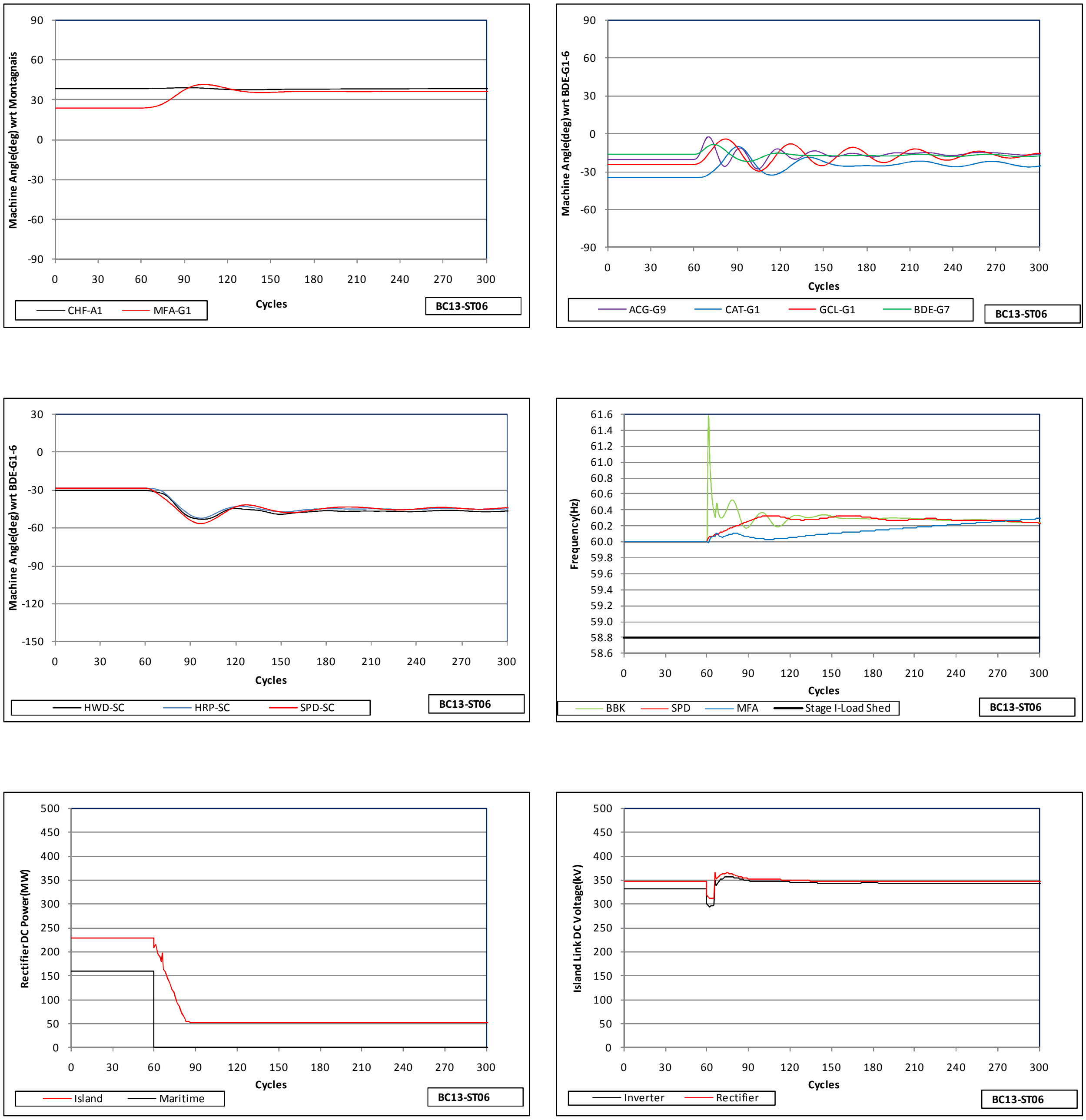
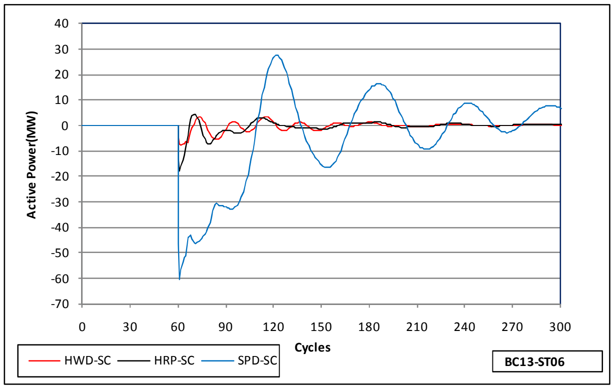
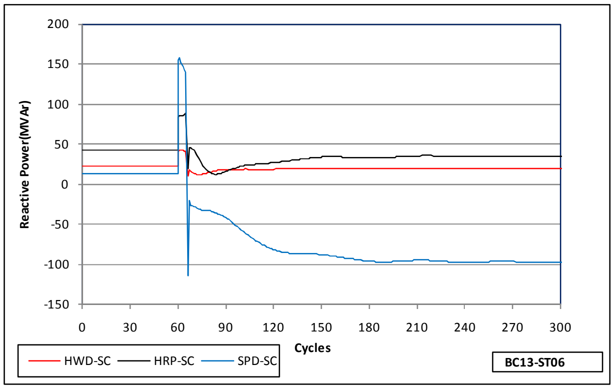
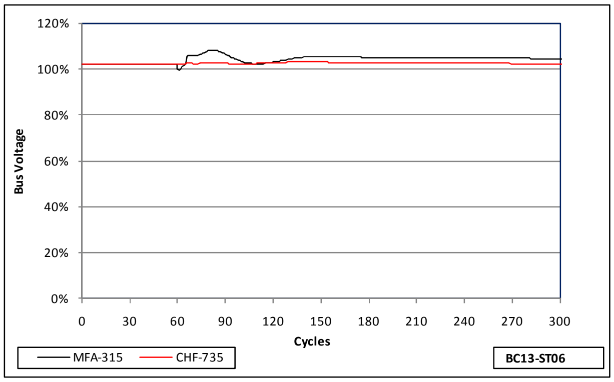

Bus Voltage
140%
120%
100%
80%
60%
40%
20%
0%
0 30 60 90 120 150 180 210 240 270 300
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST05

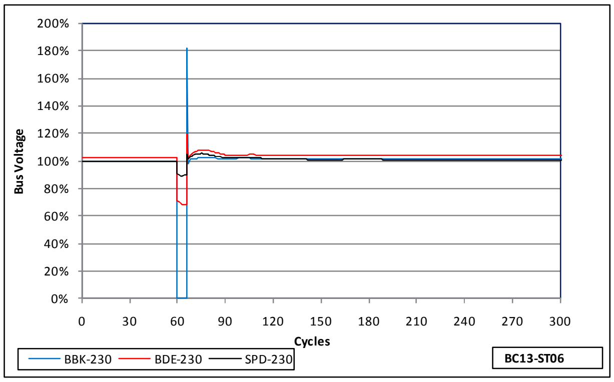
Figure 3-39: BC13-ST06, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Bottom Brook 230 kV on line to Granite Canal




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST06

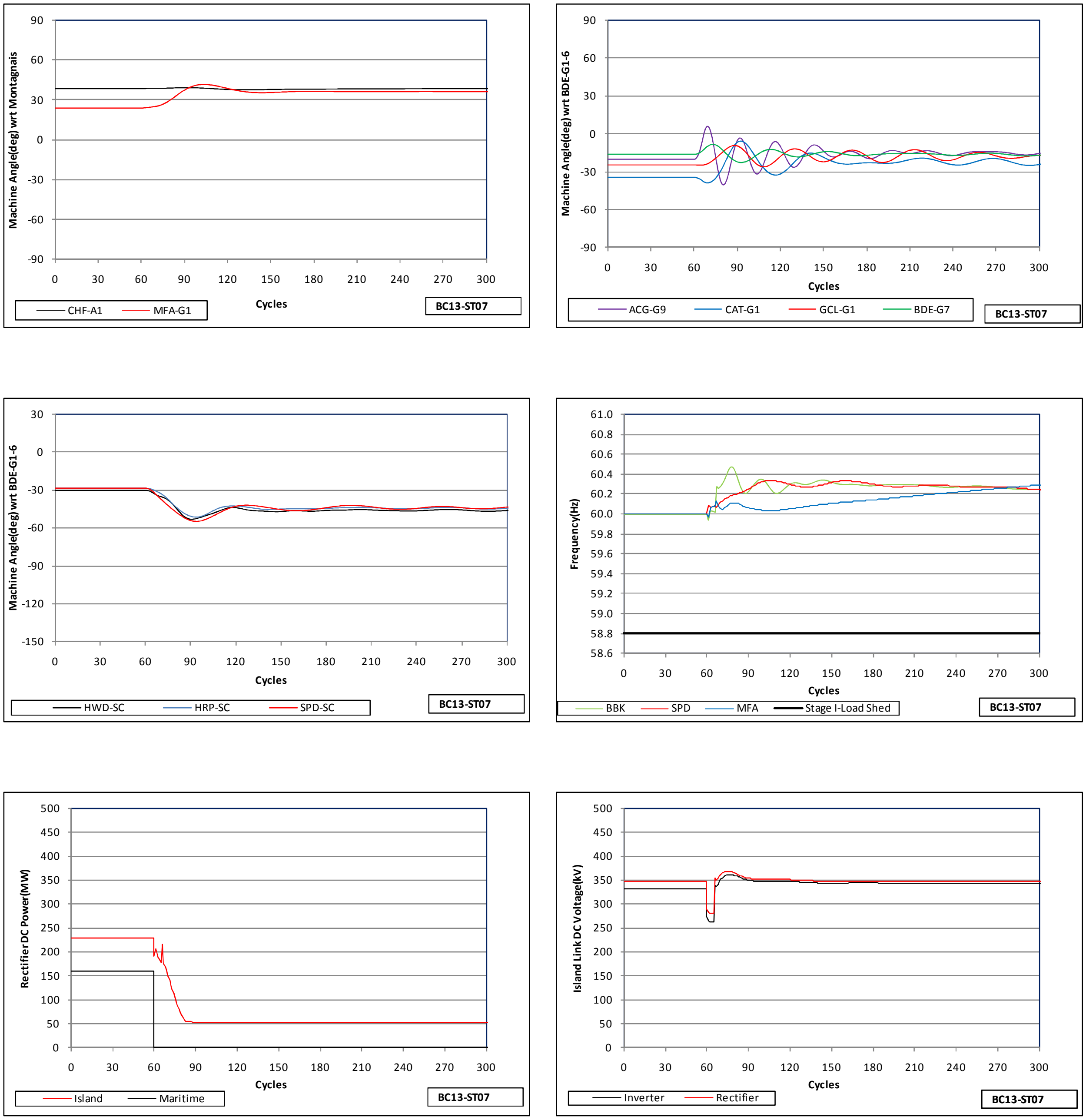

Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST06

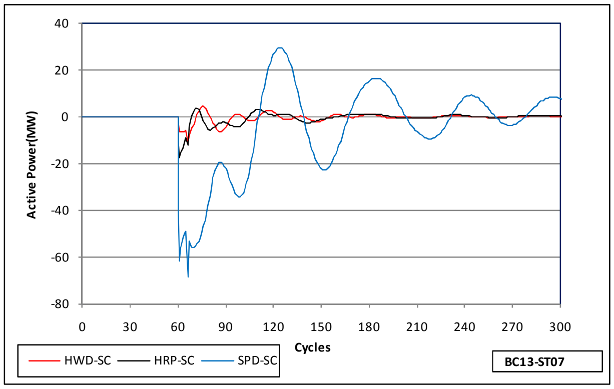

Bus Voltage
Cycles
MFA-315
CHF-735
BC13-ST06

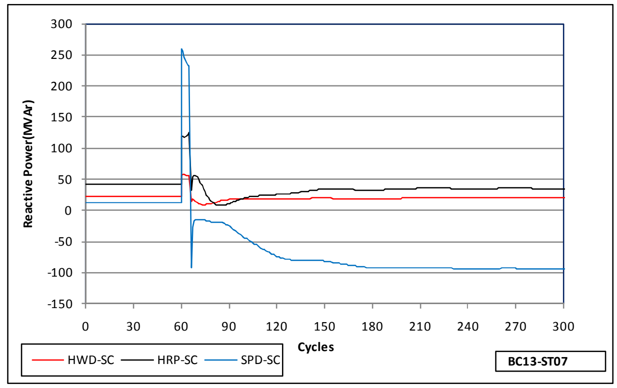

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST06

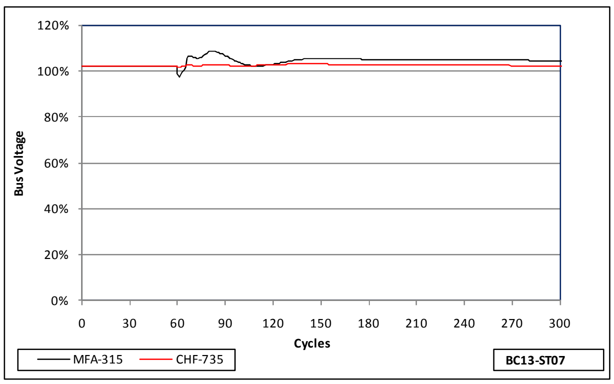
	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	111

Figure 3-40: BC13-ST07, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Stony Brook 230 kV on line to Bay d'Espoir (TL204)




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST07


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST07


Bus Voltage
Cycles
MFA-315
CHF-735
BC13-ST07

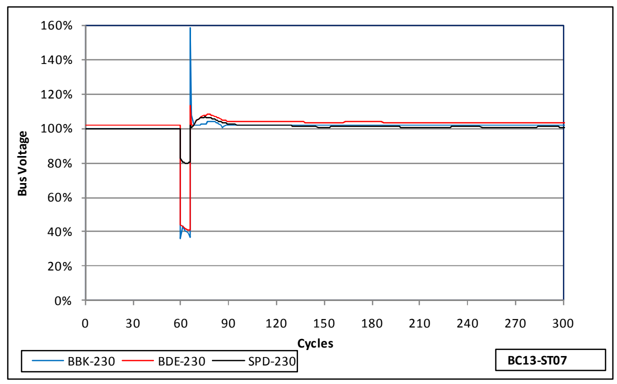
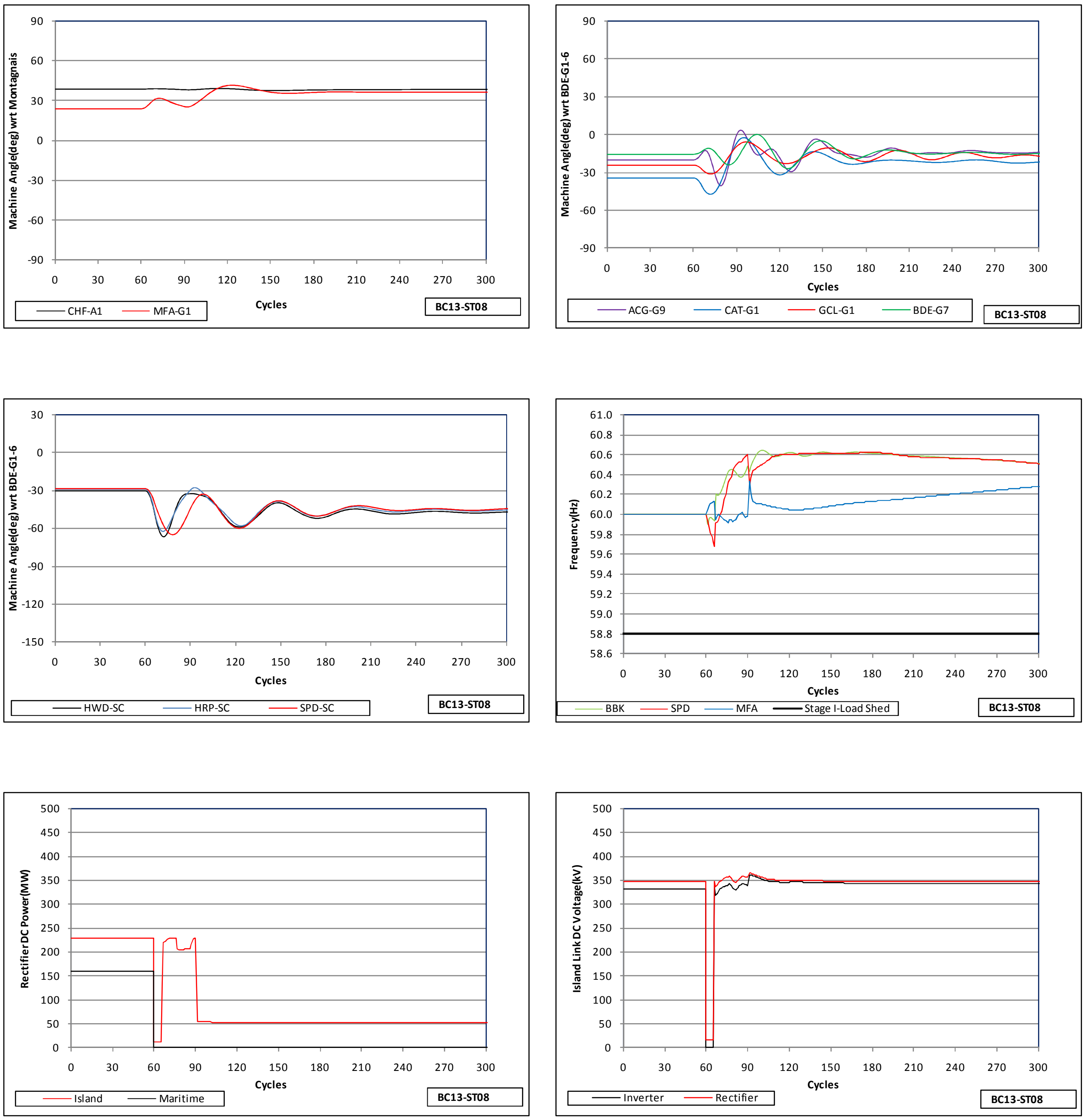
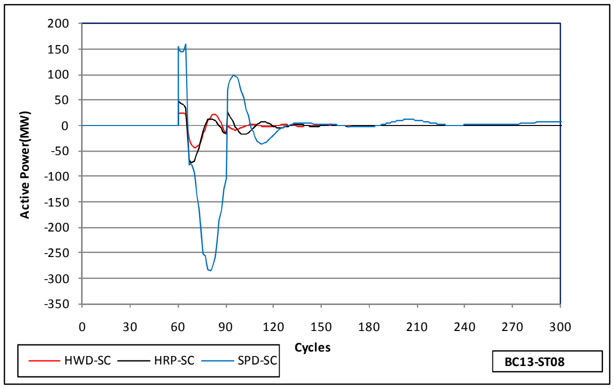
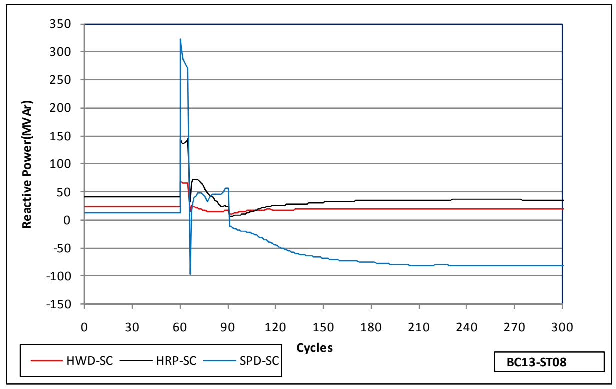
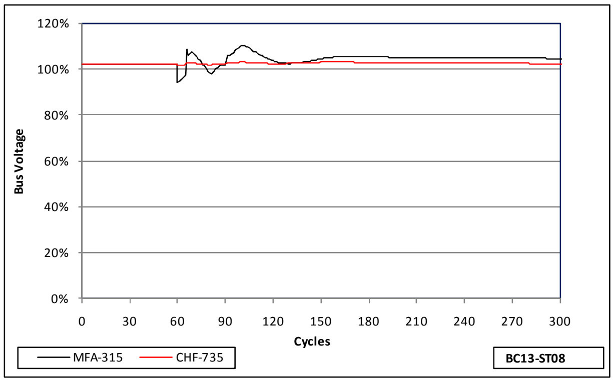

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST07

Figure 3-41: BC13-ST08, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Bay d'Espoir 230 kV on line to Sunnyside (TL202)




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST08


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST08


Bus Voltage
Cycles
MFA-315
CHF-735
BC13-ST08

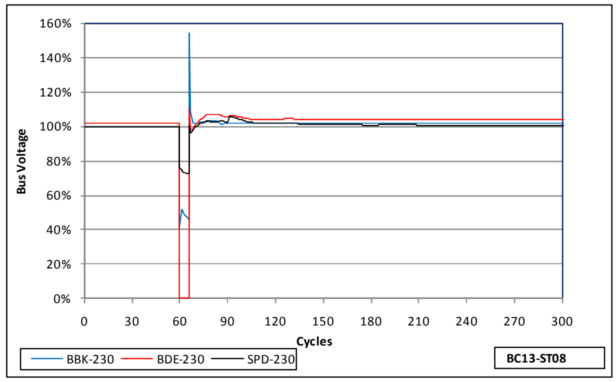
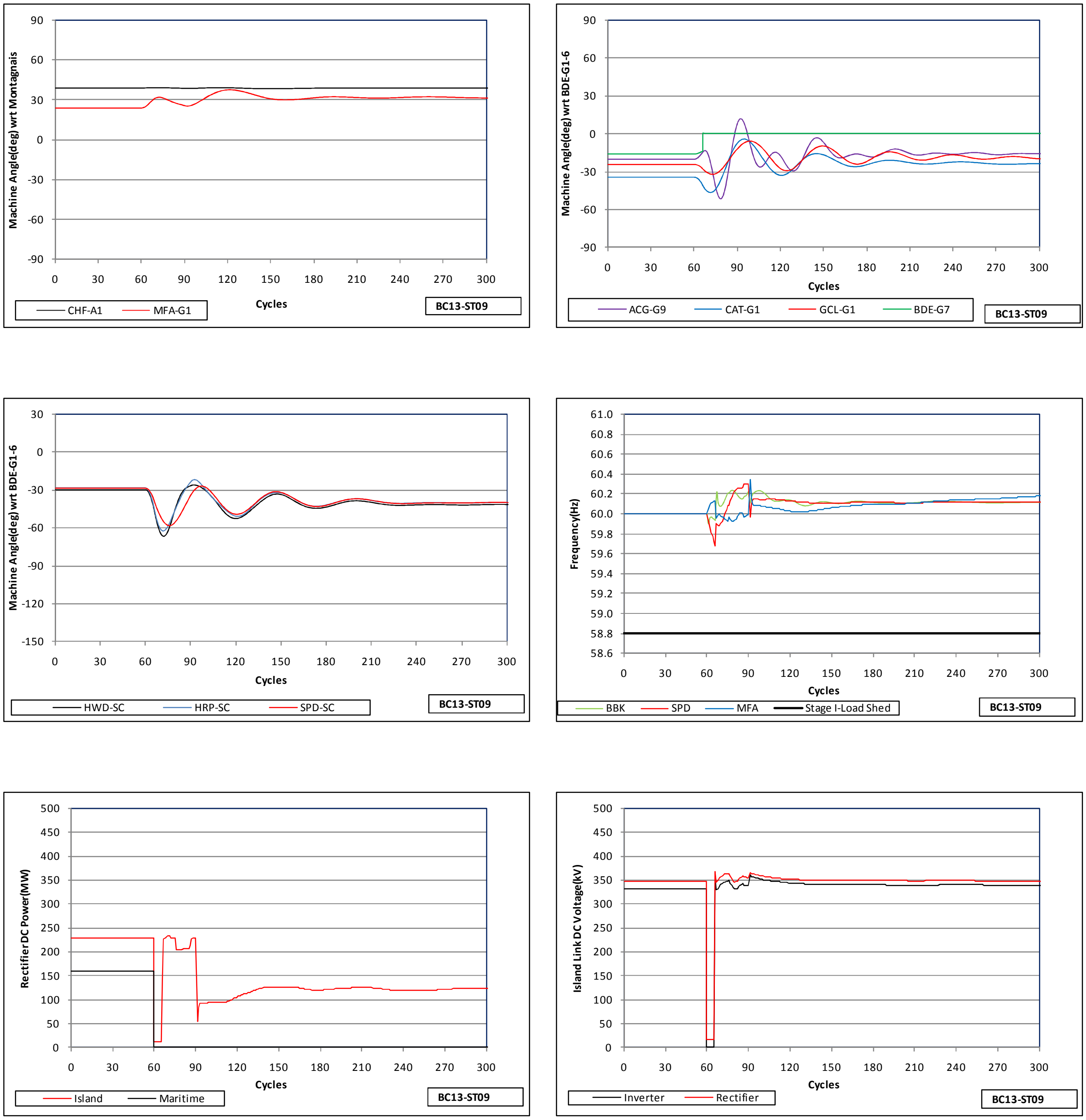
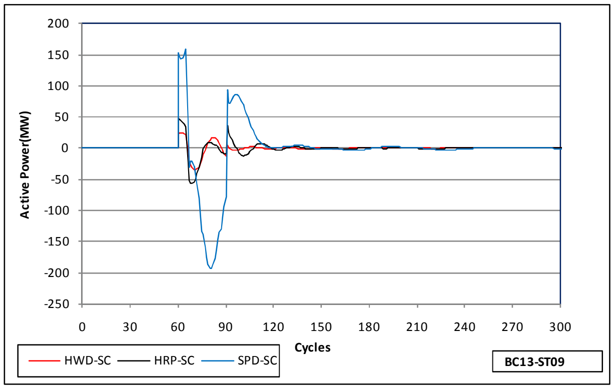
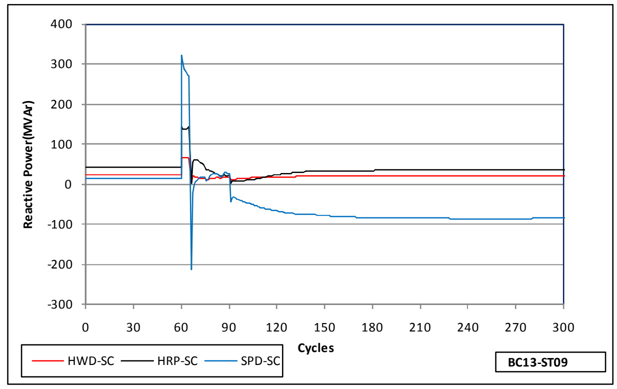
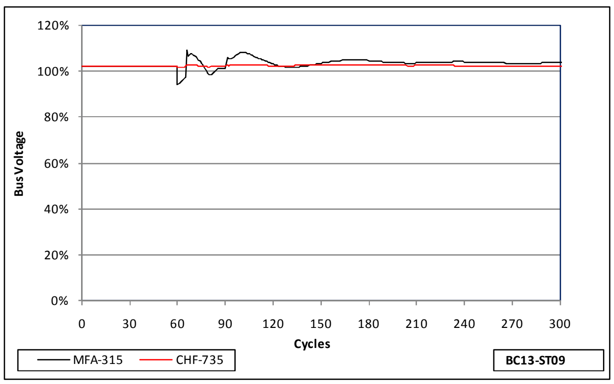

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST08

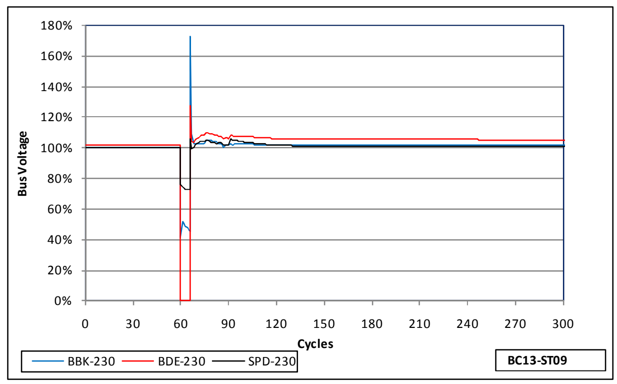
Figure 3-42: BC13-ST09, Extreme Light/Island Link 435 MW/Maritime Link 320 MW 6-cycle/3-phase Fault at Bay d'Espoir 230 kV-Generator Outage G7




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST09


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC13-ST09


Bus Voltage
Cycles
MFA-315
CHF-735
BC13-ST09


Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC13-ST09

3.5 Optimization of High Inertia Synchronous Condensers

In order to refine the selection of the high-inertia synchronous condensers at Soldiers Pond, a number of studies were conducted considering the temporary bipole fault under Scenario BC-2, which appeared to be one of the defining cases for the synchronous condenser requirements. The studies described above considered 300 MVA of synchronous condensers with an inertia constant of 7.84 kW-s/kVA. The studies below showed that the minimum requirement for the synchronous condensers was:

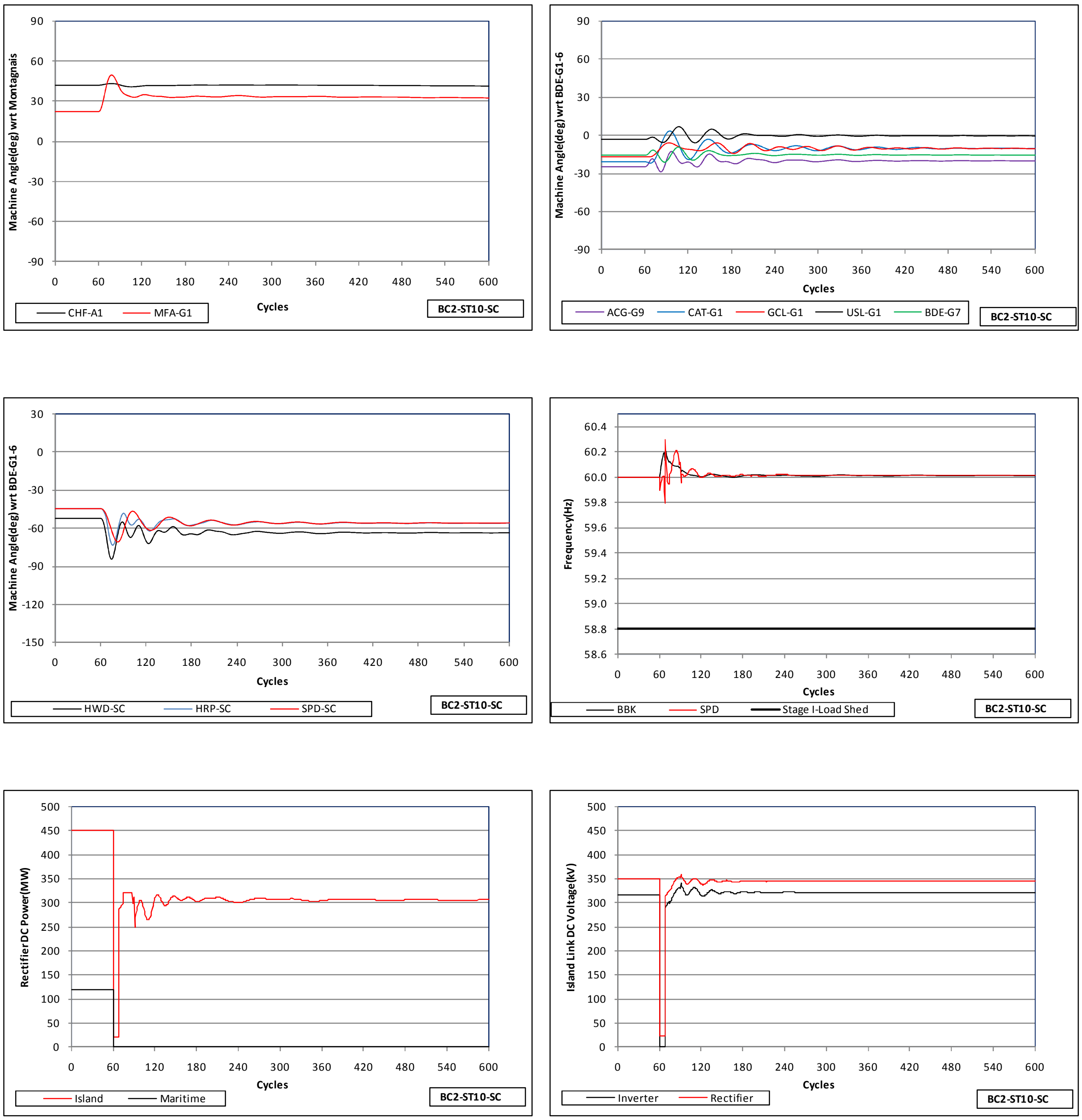
- 300 MVA of condensers with an inertia constant of 6.76 kW-s/kVA,
- 255 MVA of condensers with an inertia constant of 7.84 kW-s/kVA.

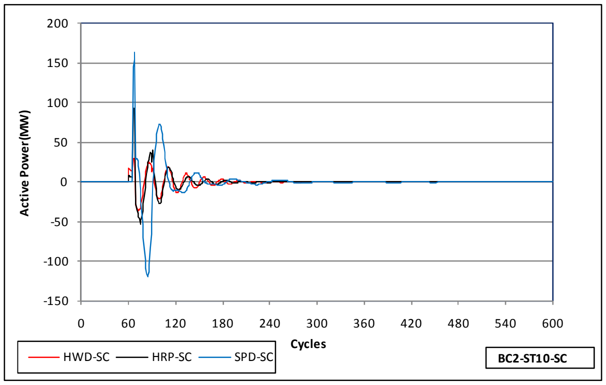
In both cases, the total inertia is approximately 2,000 MW-s.

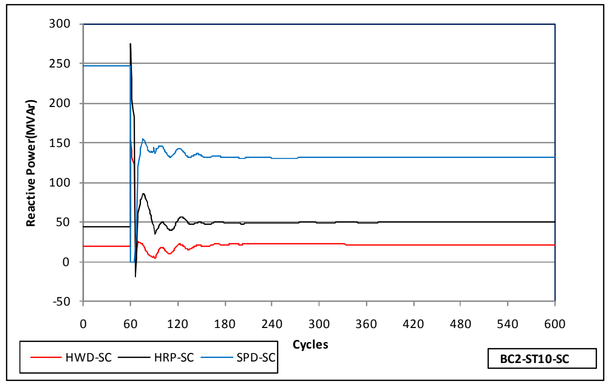
Since there will be occasions when a high-inertia synchronous condenser is not available, due to a fault or routine maintenance, it is essential to have a spare unit available. The question then arises as to whether this spare unit must be on-line at all times (hot spare) or whether it can remain off-line until required (cold spare). To assist in this decision, a study was carried out considering a 6-cycle/3-phase fault at Soldiers Pond 230 kV that resulted in the loss of 150 MVAr (H=7.84 kW-s/kVA) of synchronous condenser capacity. Faults at other locations would not result in the outage of a synchronous condenser. The results of this study are shown in Figure 3-43. It can be seen that the system recovery is satisfactory with the Maritime Link remaining in service, even though half of the synchronous condenser capacity was lost as a result of the fault. The same study was repeated with 1x300 MVAr synchronous condenser. As shown in Figure 3-44, the loss of a single 300 MVAr unit will result in system collapse.

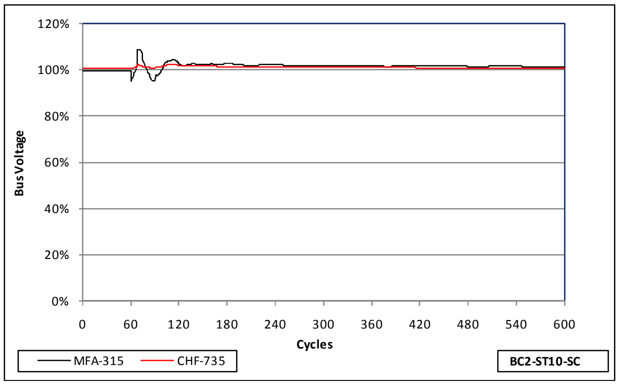
The implication of this result is that with 1x300 MVA synchronous condenser, a spare 1x300 MVAr unit would need to be operated as a hot spare. If 2x150 MVAr units are used with 1x150 MVAr spare unit, the spare unit can be used as a cold spare, resulting in a saving in losses and maintenance requirements.

Figure 3-43: BC2-ST10, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Soldiers Pond 230 kV-1x150 MVAr SC Outage




Active Power(MW)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST10-SC


Reactive Power(MVAr)
Cycles
HWD-SC
HRP-SC
SPD-SC
BC2-ST10-SC


Bus Voltage
Cycles
MFA-315
CHF-735
BC2-ST10-SC

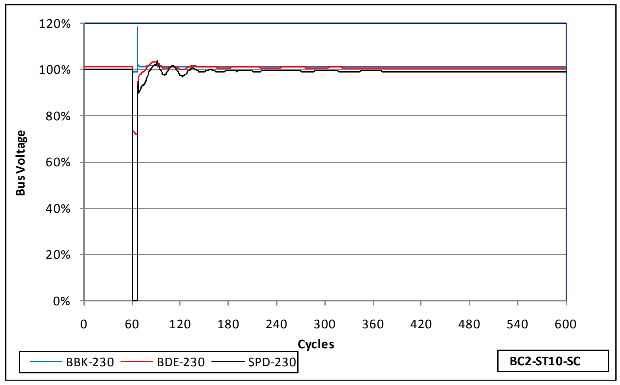
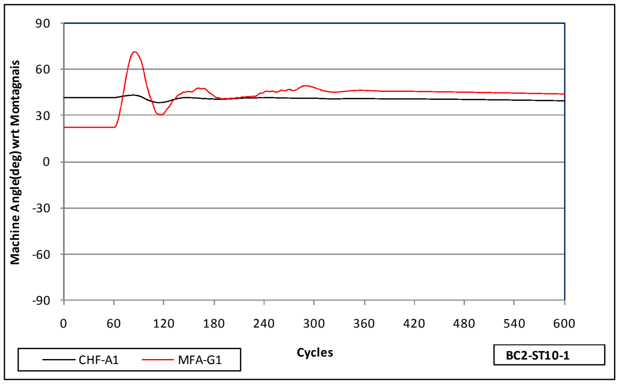
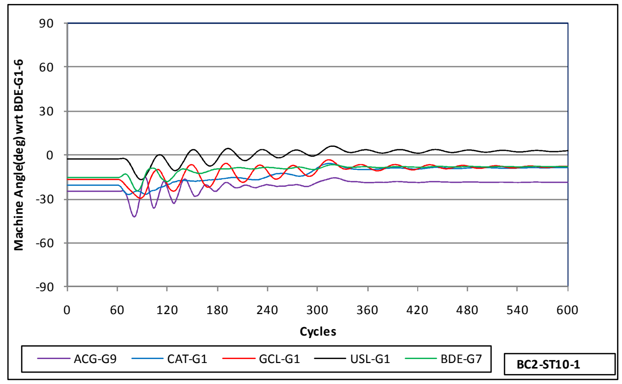
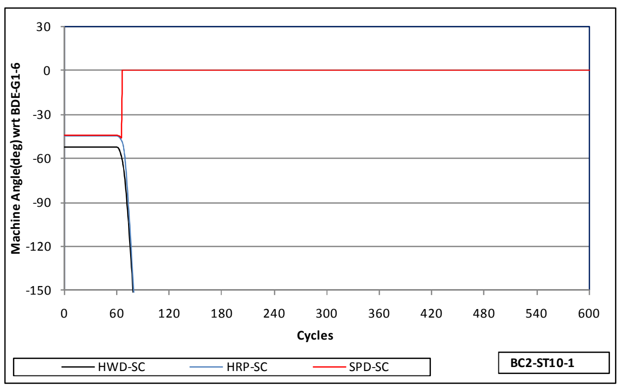

Bus Voltage
Cycles
BBK-230
BDE-230
SPD-230
BC2-ST10-SC

Figure 3-44: BC2-ST10-1, Winter Peak/Island Link 900 MW/Maritime Link 239 MW 6-cycle, 3-phase Fault at Soldiers Pond 230 kV-1x300 MVAr SC Outage







3.6 Sensitivity of the Temporary Bipole Fault Re-Start Time

In the studies above, for a temporary bipole fault, the Island Link was blocked for 12-cycles/200 ms. This blocking time was developed from an allowance of 1.5-cycles/25 ms to detect the fault and change the operating mode of the converters to reduce the dc current to zero and 10.5-cycles/175 ms de-ionization time to ensure that the fault arcs had extinguished before re-starting the converters in normal operating mode. The starting time of the converters was approximately 6 – cycles/100 ms resulting in an overall time of 18-cycles/300 ms between fault initiation and a return to normal power. The base case considered 2x150 MVAr high-inertia synchronous condensers at Soldiers Pond.

Since the time required for de-ionization cannot be accurately determined and can vary with the nature of the fault, a range of studies were carried out to examine the maximum time that could be tolerated before the dc was re-started as a function of the number of high-inertia synchronous condensers installed at Soldiers Pond.

A series of study results are presented in Figure 3-45. For each of these cases, the re-start time was increased until the post-fault recovery was unsuccessful

For case BC2-ST01-3, 3x150 MVAr synchronous condensers were considered at Soldiers Pond; the second case (BC2-ST01-4) considered 4x150 MVAr units.

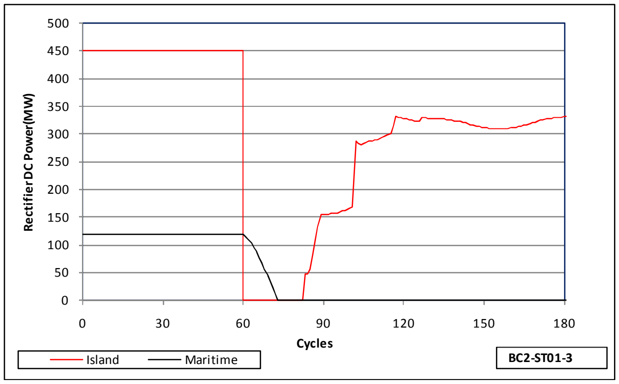
In the first case the re-start time was increased until 23-cycles/380 ms after fault inception and the dc power was ramped back up to 320 MW per pole; in the second case the re-start time was increased to 45-cycles/750 ms and the dc power was ramped back to 450 MW per pole following the re-start.

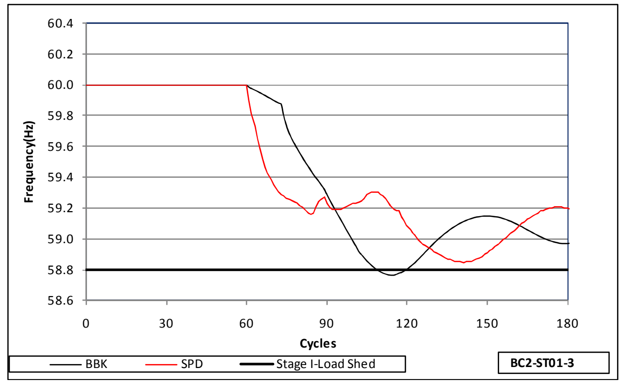
In both cases, the frequency at Soldiers Pond decreased to just above the first stage load shedding frequency of 58.8 Hz. However, it can be seen that the limiting factor is, in fact, the frequency to the west of Bay d'Espoir as seen by the frequency at Bottom Brook, which in the second case fell below the load shedding threshold frequency. A practical limit would therefore be less than the 45-cycles/750 ms considered in the study, as shown below:

- With 2x150 MVAr synchronous condensers:
  - maximum re-start time = 12-cycles/200 ms
- With 3x150 MVAr synchronous condensers”
  - maximum re-start time = 23-cycles/380 ms
- With 4x150 MVAr synchronous condensers”
  - maximum re-start time = 34-cycles/567 ms

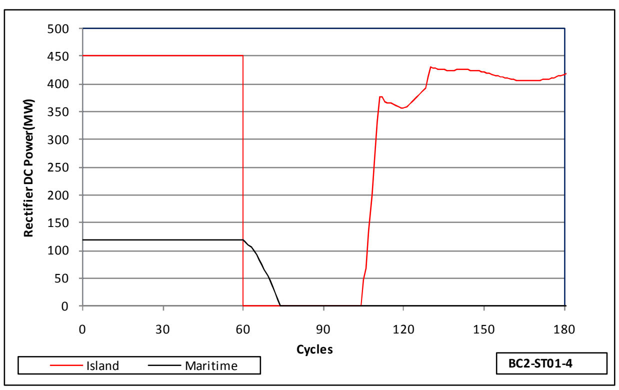
Figure 3-45: BC2-ST01-3/4, Winter Peak/Island Link 900 MW/Maritime Link 239 MW Temporary Bipole Fault-Synchronous Condenser Capacity at Soldiers Pond

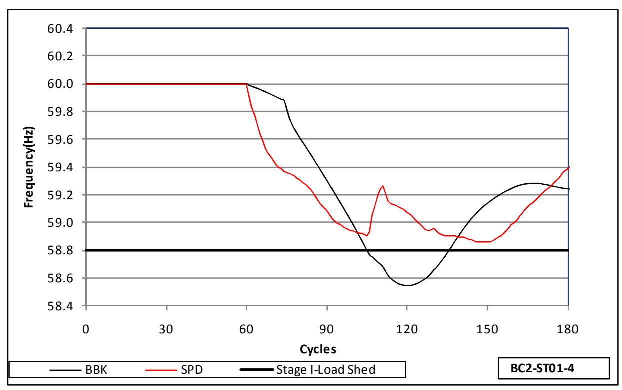
3-150 MVAr Synchronous Condensers





4-150 MVAr Synchronous Condensers





4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Introduction

This report presented the results of the stability studies carried out to examine the dynamic performance of the ac and dc systems including the HVdc interconnections between Muskrat Falls and Soldiers Pond (Island Link) and between Bottom Brook and the Nova Scotia power system (Maritime Link). The present Design Basis considers, for the Island Link, a dc voltage level of ±350 kV and a nominal bipole rating of 900 MW and, for the Maritime Link, a dc voltage level of ±200 kV and a nominal bipole rating of 500 MW. This is interpreted to mean that these rated power levels and rated voltages apply at the rectifier ends (Muskrat Falls and Bottom Brook).

The Island Link will be essentially uni-directional from Labrador to Newfoundland, although there will be nothing in the design of the link to prevent operation in the reverse direction. The Maritime Link is required to have a 500 MW continuous capability in bipolar mode in both directions.

The connection to the TransEnergie 735 kV system in Quebec was represented by a simple equivalent at the Montagnais Substation. The Emera system in Nova Scotia was represented by a simple equivalent at the inverter station of the Maritime Link. The ac system between Churchill Falls and Muskrat Falls and the Island ac system were modelled in detail.

Starting from the base case scenarios provided by Nalcor, the present studies were designed to determine the dynamic performance of the ac/dc systems following major faults on either the ac or dc systems. The 6-cycle/3-phase faults considered resulted in the outage of a single element of either the ac or dc system. Because of the relative importance of the Island Link in the overall supply capability of the Island load, the temporary loss of both poles of the Island Link bipole was also considered.

4.2 Study Objectives

The stability studies were designed to achieve the following objectives:

Objective 1

To verify that the interconnected systems of Newfoundland and Labrador with interconnections into Quebec and Nova Scotia can operate satisfactorily through a wide range of faults resulting in outages on the transmission network.

Objective 2

To determine the requirements in terms of control functions that will be required on the Island and Maritime dc links,

Objective 3

To determine the requirements for additional equipment, in the form of static var compensators and/or synchronous condensers, that will be required at or near the converter stations to ensure satisfactory dynamic performance,

Objective 4

To verify that load shedding on the Island will not occur for the range of fault cases examined,

Objective 5

To determine any operating requirements that must be applied to the Island and Maritime dc links to ensure stable operation.

4.3 Results of the Studies

A major change from previous studies centres on the criterion that, in the event of a major disturbance on the Island or on the Island Link, the export over the Maritime Link can be discontinued. This means that the export over the Maritime Link is acting as a form of spinning reserve for the Island system and allows the Island system to recover quickly and successfully from all the faults considered in this study. This method of operation was simulated by using a frequency controller on the Maritime Link at the Bottom Brook converter to reduce the dc power level when the frequency at Bottom Brook falls below 60 Hz. Although not available in the PSS®E model, this type of controller can operate with a dead-band to allow for normal frequency fluctuations.

For faults that occur on the Bay d'Espoir 230 kV bus or any other 230 kV bus to the west of Bay d'Espoir and for a temporary bipole fault on the Island Link, the voltage and/or frequency depressions at the Bottom Brook 230 kV converter bus will result in blocking of the Maritime Link. In some cases, faults at Soldiers Pond would also require that the export over the Maritime Link be temporarily suspended.

In order to survive a temporary bipole fault on the Island Link or a 6-cycle/3-phase fault at Muskrat Falls, it was found necessary to have 300 MVAr of high-inertia (H=7.84 kW-s/kVA) synchronous condensers at the Soldiers Pond 230 kV converter bus, in addition to two synchronous condensers at Holyrood. The Holyrood synchronous condensers have inertia constants of 1.182 kW-s/kVA and 1.29 kW-s/kVA and contribute approximately 230 MW-s each to the total inertia of the system. The Soldiers Pond synchronous condensers contribute 2,350 MW-s.

In order to survive a 6-cycle/3-phase fault at Bay d'Espoir during peak load periods only, it was necessary to have either:

- 450 MVAr of high-inertia synchronous condensers at Soldiers Pond and the three synchronous condensers at Holyrood to provide support to the voltage at Bay d'Espoir, or

- ±250 MVAr of reactive support at Bay d'Espoir together with 300 MVAr of high-inertia synchronous condensers at Soldiers Pond and the three synchronous condensers at Holyrood.

The application of 50% series compensation to the 230 kV lines from Bay d'Espoir to Sunny Side [TL203 & TL206] and to Western Avalon [new line] did not provide sufficient reactive support to enable the system to survive.

Objective 1

The study results confirmed that the interconnected systems of Newfoundland and Labrador with interconnections into Quebec and Nova Scotia can operate satisfactorily through a wide range of faults resulting in outages on the transmission network.

Objective 2

The studies indicated that some form of frequency control will be required on both the Soldiers Pond and Bottom Brook converters. The frequency controller at Soldiers Pond would act to increase the dc power on the Island Link for a fall in frequency on the Island. For any fault that results in blocking of the Island Link, the frequency controller at Soldiers Pond must be disabled for a minimum period of 500 ms following the block and until the time when the frequency at Soldiers Pond is 59.9 Hz or higher. The frequency controller at Bottom Brook would act to decrease the dc power on the Maritime Link for a fall in frequency on the Island. It should be noted that the application of a frequency controller at the Bottom Brook converter will preclude the use of the Maritime Link for frequency control in Nova Scotia as frequency controllers cannot be used simultaneously at both ends of a dc link. In addition, for a temporary bipole fault on the Island Link, an increase in the high-inertia synchronous condenser capacity at Soldiers Pond, would allow for a longer de-ionization period to be considered for the fault. With 300 MVAr of synchronous condenser capacity at Soldiers Pond, the maximum time permitted until re-start after a bipole fault is 12-cycles/200 ms. With 450 MVAr of synchronous condenser capacity, the re-start time can be extended to 380 ms.

In many of the cases examined, it was found necessary, following a block of the Island Link during ac system faults, to ramp the dc power back up in a staged manner. The use of a voltage-dependent recovery control in which the rate of ramp-up and the target dc power level is determined by the converter ac bus voltage is recommended.

Objective 3

The studies indicated that a minimum of 300 MVAr of high-inertia synchronous condenser capacity will be required at the Soldiers Pond 230 kV converter bus. The total inertia requirement is approximately 2,000 MW-s and, allowing for a spare unit, could be achieved with 2x300 MVAr units; the spare unit running as a hot spare, or with 3x150 MVAr units; the spare unit being operated as a cold spare. Since there is a requirement for synchronous condensers at Soldiers Pond, no advantage is seen in considering VSC technology for this converter station.

The defining cases in terms of synchronous condenser capacity requirements at Soldiers Pond are those cases that involve a three-phase fault at Bay d'Espoir during the winter peak load period. In such cases, the voltage recovery at Bay d'Espoir is relatively weak and this is reflected in the voltage at Soldiers Pond and all the substations in between. With 300 MVAr of synchronous condenser capacity at Soldiers Pond, the voltage at Soldiers Pond recovers within the normal 80% post-fault criterion currently is use in the NLH system and the system recovery is stable and well damped. However, an ac voltage of less than 90% involves a significant risk of commutation failure for the inverter when it attempts to re-start. In order to assist the voltage recovery, it was necessary to increase the synchronous condenser capacity at Soldiers Pond to 450 MVAr and connect all three synchronous condensers at Holyrood.

The low probability of a three-phase fault and the fact that this requirement only applies during the winter peak load period, raises the question of the total capacity requirements for the synchronous condensers. The minimum synchronous condenser capacity of 300 MVAr could be achieved with 3x150 MVAr units, which allows for one spare unit. This would mean that during the winter peak load period, either the risk of a three-phase fault at Bay d'Espoir is accepted or the third (spare) synchronous condenser is connected. With such an operating philosophy, maintenance work on any of the synchronous condensers at Soldiers Pond, Holyrood and Hardwoods could only be scheduled outside the winter peak load period. In the event of a synchronous condenser fault, that may involve a long repair time that extends into the winter season, the system would be placed at risk for a three-phase fault at Bay d'Espoir. If such a fault occurred, extensive high-speed load shedding would be required to enable the system to recover.

At Bottom Brook, dynamic reactive power control will be required to control the temporary over-voltages that will occur when the Maritime Link blocks due to low voltage and/or low frequency. Under extreme light load conditions with a 320 MW export on this link, the temporary over-voltage can reach as high as 180% and must be reduced quickly to avoid equipment damage. This dynamic reactive power control could be achieved either in the form of a static var compensator (+320/-100 MVAr) or in the form of VSC technology for the Bottom Brook converter. The use of 2x250 MW VSC converters at Bottom Brook would provide up to 125 MVAr of reactive power control and an additional 195 MVAr of shunt compensation, in the form of an SVC or switched shunt capacitors would be required.

Bearing in mind the impact of a three-phase fault at Bay d'Espoir and the inherent reactive support that can be provided by a VSC converter for the Maritime Link, raises the question of the benefits that may be associated with locating the Maritime Link converter at Bay d'Espoir instead of at Bottom Brook. Although outside the scope of these studies, such a re-location would significantly affect the synchronous condenser capacity required at Soldiers Pond. For faults at Bay d'Espoir, which would require an additional 150 MVAr of high-inertia synchronous condenser at Soldiers Pond, the location of the Maritime Link converter of the VSC type would provide sufficient reactive support at Bay d'Espoir to enable the system to survive a three-phase fault at Bay d'Espoir with only 300 MVAr of high-inertia synchronous condenser capacity at Soldiers Pond.

Objective 4

With the addition of the high-inertia synchronous condensers at Soldiers Pond and the control functions described above, there will be no necessity for load shedding on the Island for the range of faults considered. It will be necessary to re-evaluate a small number of fast-acting, rate-of-change-of-frequency load shedding settings that are presently enabled on the Island system.

Objective 5

The only restrictions identified on the operating modes of the Island and Maritime Links were as follows:

- For many of the fault cases examined, it was found necessary to reduce the export over the Maritime Link to zero to ensure a satisfactory recovery of the Island system. The Maritime Link can be re-started manually after the Island system has settled down at a level commensurate with the Muskrat Falls and Island system capabilities following the fault.
- The studies showed that following a major disturbance on either the Island Link itself or on the Island ac system, the Island Link must be re-started in a controlled manner to avoid the risk of low voltages at the Soldiers Pond inverter bus that might lead to commutation failure of the inverter.

It was seen that for certain faults and at specific load levels, the export over the Maritime Link would need to be temporarily suspended. It may prove to be more convenient to adopt an operating philosophy that would temporarily suspend this export for all faults on the Island Link and Island 230 kV ac system. In any event, it will be necessary for the export level over the Maritime Link to be provided to the controllers of the Island Link to enable the required power level for a re-start of the Island Link to be determined.

4.4 Recommendations

Based on the results of the studies described above, the following recommendations are made:

- LCC converters to be installed for the LIL Link due to the long duration of dc fault clearance which would also require high-inertia synchronous condensers to avoid system collapse.
- 3x150 MVAr high-inertia (7.84 kW-s/kVA) synchronous condensers be installed at the Soldiers Pond converter station to provide active and reactive power support to the Island system. The normal requirement would be to have two of these units connected at all times with the third unit used as a cold spare. This

would allow maintenance to be carried out on the units at Soldiers Pond as well as those at Holyrood and Hardwoods.

- The re-start of the Island Link be controlled to account for the temporary shutdown of the Maritime Link following dc or 230 kV ac faults on the Island system. The control should take the form of a limit on the dc power level to maintain the 230 kV ac voltage at Soldiers Pond at 90% or above.

- Consideration be given to re-locating the VSC converter for the Maritime Link from Bottom Brook to Bay d’Espoir. This would avoid the need to reinforce the 230 kV system between Bay d’Espoir and Bottom Brook and would allow the Island system to survive a three-phase fault at Bay d’Espoir without having to install a fourth high-inertia synchronous condenser at Soldiers Pond.

- During periods when lightning activity is forecast along the route of the Island Link, the starting up of the third high-inertia synchronous condenser at Soldiers Pond would increase the maximum time delay that could be tolerated before re-starting the Island Link after a temporary bi-pole fault on the Island Link from 12-cycles/200 ms to 23-cycles/380 ms. This would allow more time for the fault path to de-ionize.

APPENDIX A

BASE CASE LOAD FLOWS

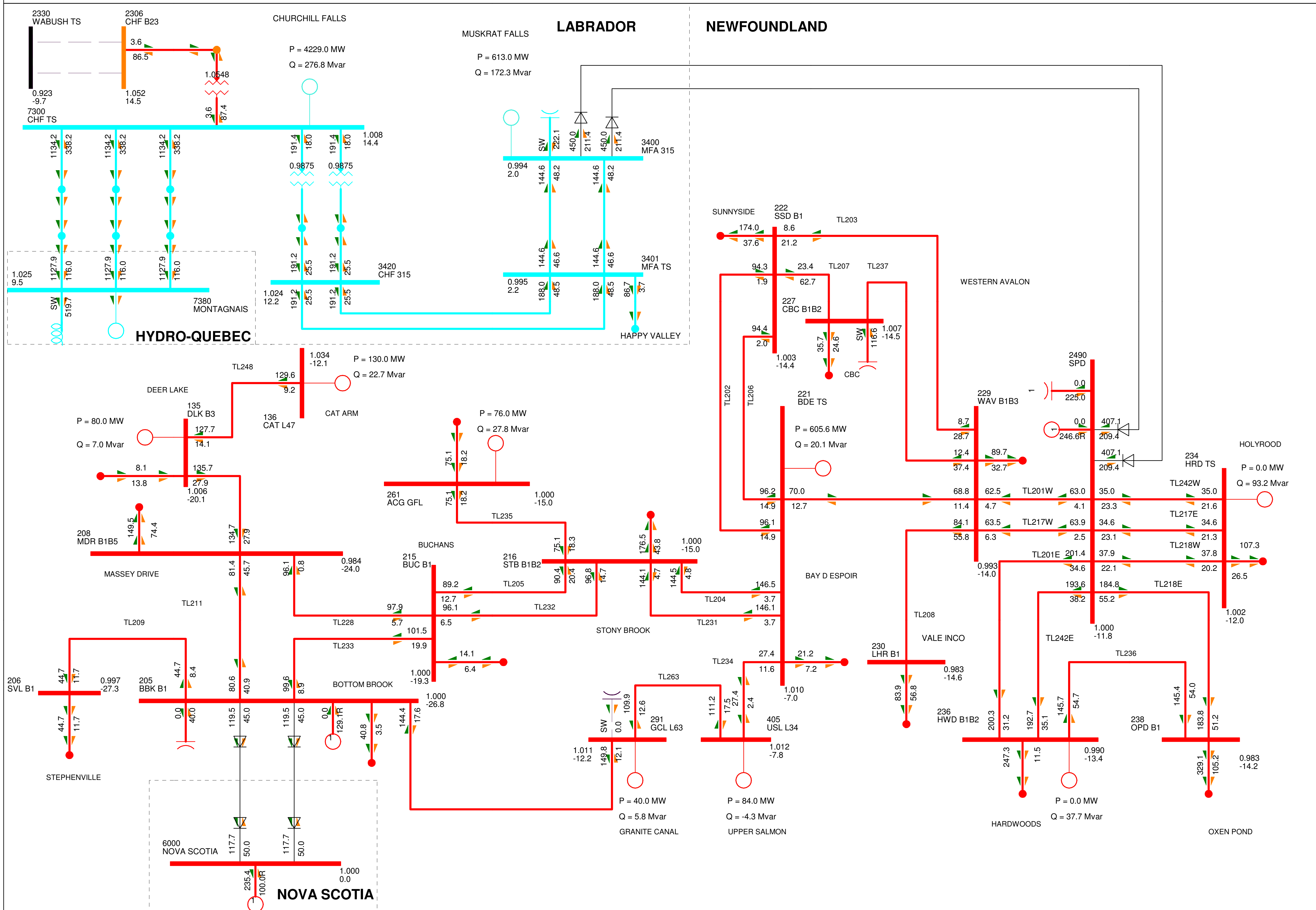
List of Figures (Appendix A)

Attachment A-1

BC2 – Winter Peak 2017

1552 MW, 814 MW Import and 239 Export

BC2 - WINTER PEAK 2017, 1552 MW, 814 MW IMPORT AND 239 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

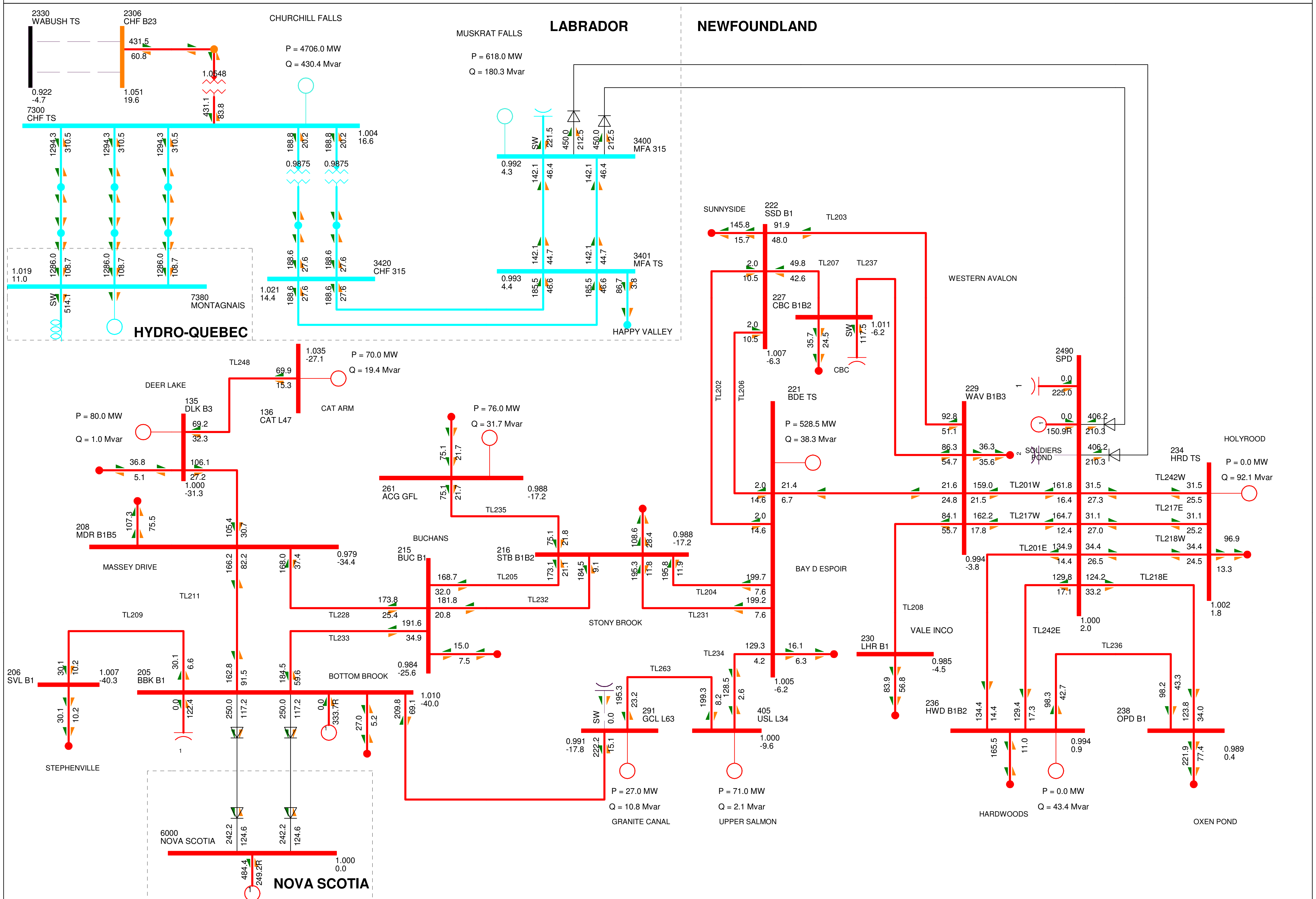
- Base Case
- Generation: Maximum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A-2

BC7 – Spring / Fall Intermediate 2017

1100 MW, 814 Import and 500 Export

BC7 - SPRING/FALL INTERMEDIATE 2017, 1100 MW, 814 MW IMPORT AND 500 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEB
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

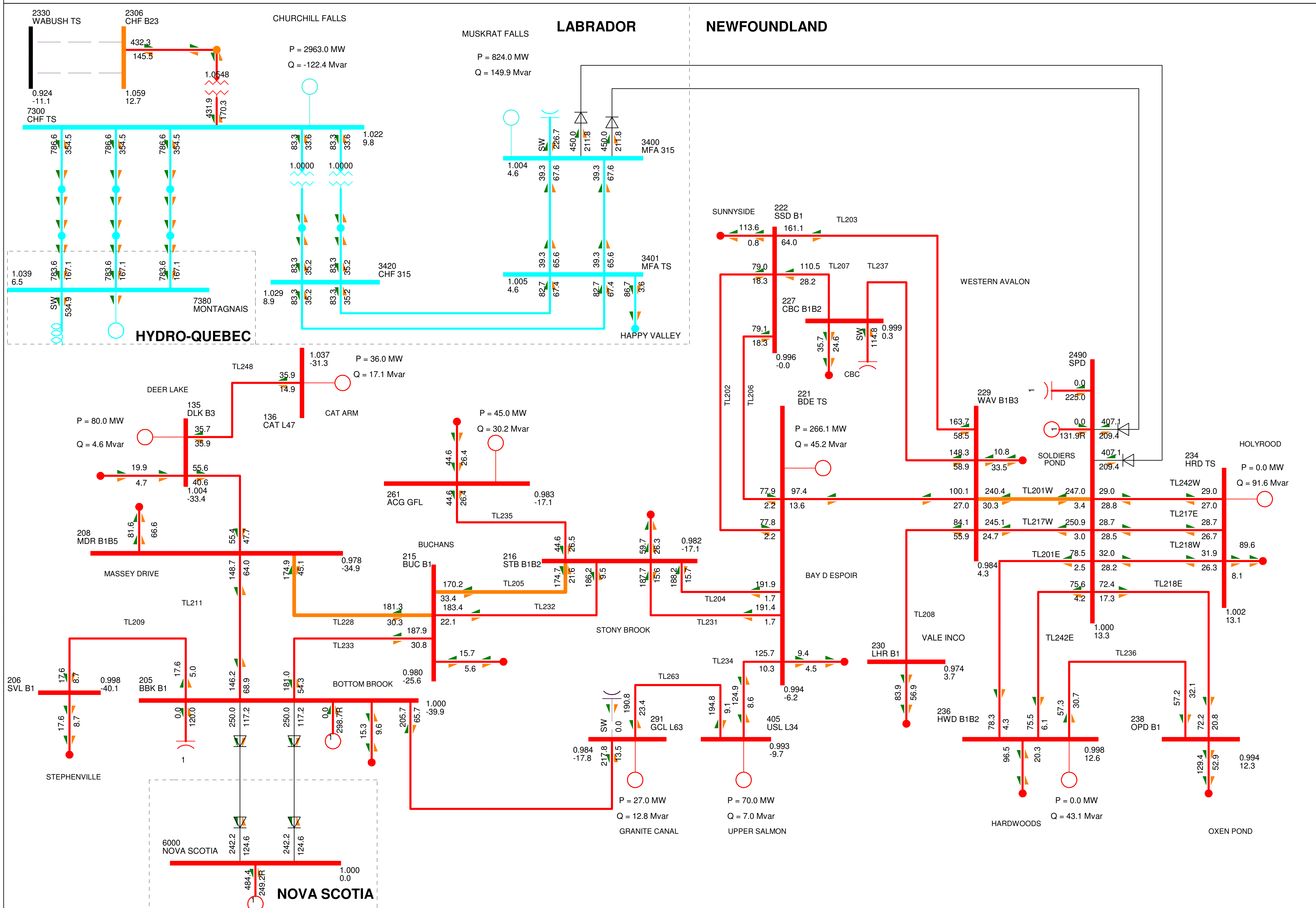
- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A-3

BC10 – Summer Day Light 2017

700 MW, 814 MW Import and 500 MW Export

BC10 - SUMMER DAY LIGHT 2017, 700 MW, 814 MW IMPORT AND 500 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

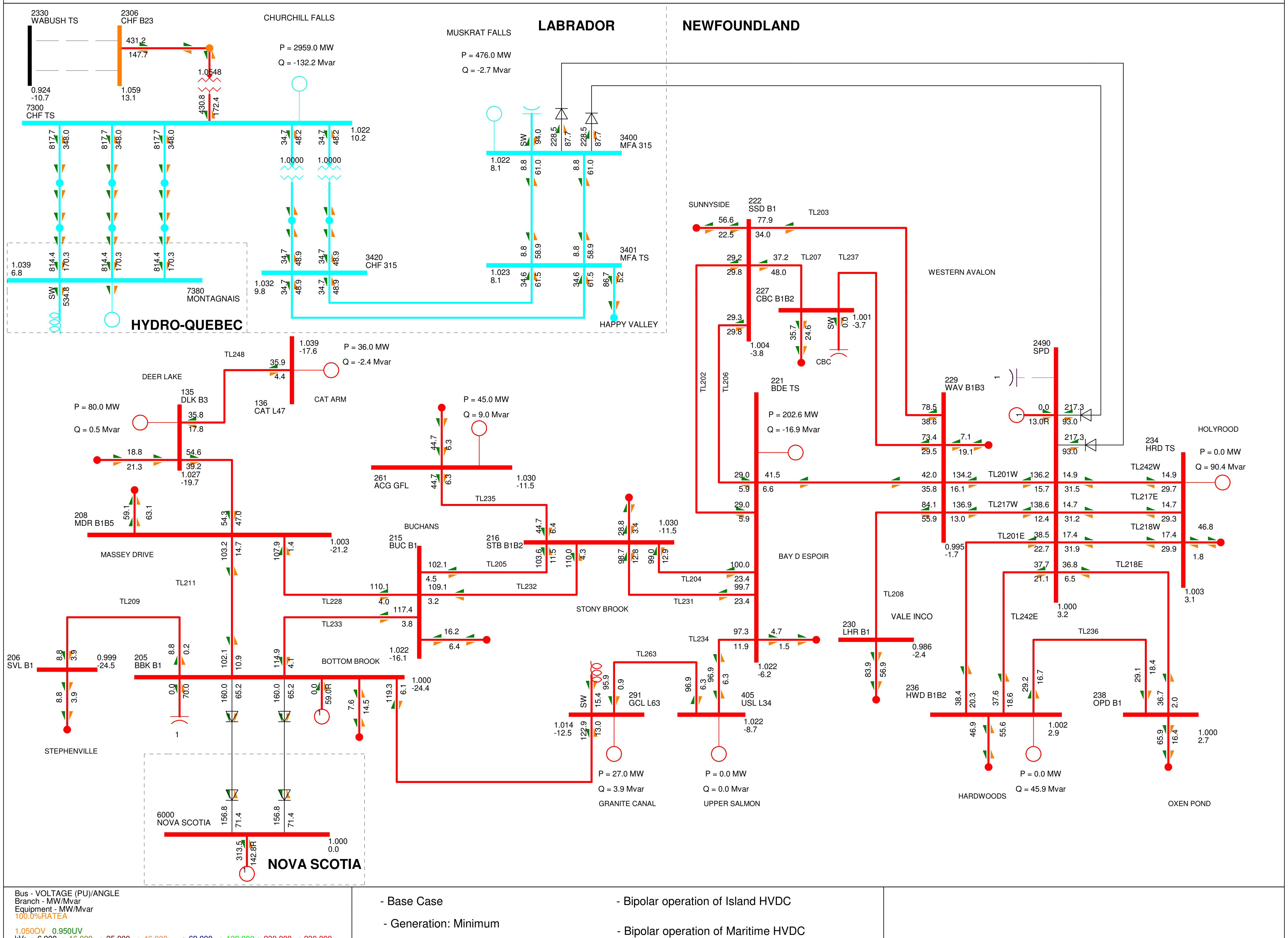
- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A-4

BC 13 – Summer Night Extreme Light 2017

420 MW, 435 MW Import and 320 MW Export

BC13 - SUMMER NIGHT EXTREME LIGHT 2017, 420 MW, 435 MW IMPORT AND 320 MW EXPORT



- Base Case
- Generation: Minimum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

APPENDIX B

SYSTEM MODELS

SNC·LAVALIN	STABILITY STUDIES	Revision		
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	Page
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	B-1

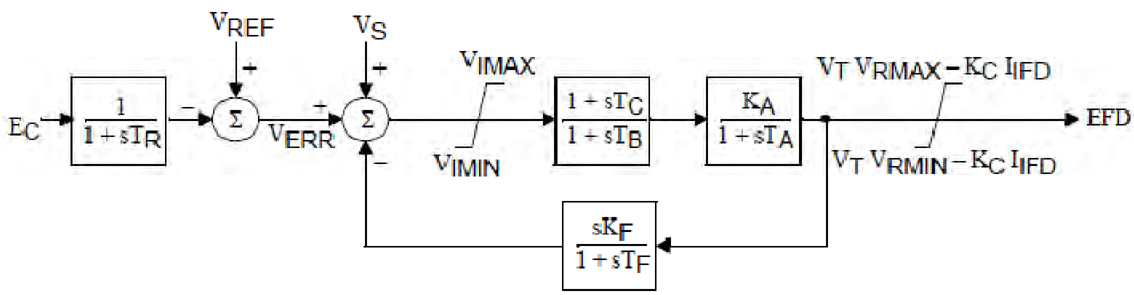
Table B-1: Generator Dynamic Data

	Unit-MVA	Td0'	Td0"	Tq0'	Tq0"	H	Xd	Xq	Xd'	Xq'	Xd"	Xl	S1.0	S1.2
		(s)	(s)	(s)	(s)	(kW-s/kVA)	(pu on Machine Rating)							
THERMAL UNITS														
Soldiers Pond High Inertia Synchronous Condenser	+300/-165	11	0.08	-	0.29	7.84	1.24	0.85	0.27	-	0.165	0.09	0.04	0.14
Stephenville GasTurbine #1/2	63.5	11	0.05	1.0	0.060	2.06	2.1446	1.9551	0.1706	1.2	0.1584	0.1407	0.117	0.306
Holyrood Unit #1/2	194.4	3.845	0.035	1.0	0.060	1.182	2.1142	2.045	0.2859	0.4787	0.1923	0.1607	0.1335	0.638
Holyrood Unit #3	177.2	6.8	0.06	1.0	0.060	1.29	2.15	1.94	0.26	0.55	0.22	0.1152	0.078	0.254
Hardwoods Gas Turbine #1/2	63.5	10.2	0.04	1.0	0.060	2.06	1.82	1.67	0.14	0.121	0.102	0.091	0.1581	0.3348
NLP Greenhill Gas Turbine	31.1	7.3	0.038	1.0	0.060	1.093	1.72	1.62	0.174	0.3475	0.139	0.11	0.285	0.7
CBP&P Primary Refiner 1P/3P/4P/5P/6P	10.2	1.001	0.05	1.0	0.050	1.256	1.46	1.4	0.3	0.36	0.2	0.07	0.1	0.5
CBP&P SecondaryRefiner 1S/2S/3S/4S/5S/6S	10.2	1.001	0.05	1.0	0.050	1.433	1.18	1.13	0.27	0.29	0.17	0.06	0.1	0.5
CBP&P Rejects Refiner R5/R6/R7	10.19	1.001	0.05	1.0	0.050	1.433	1.18	1.13	0.27	0.29	0.17	0.06	0.1	0.5
CBP&P Steam Unit-G2	21.8	5.246	0.033	0.2	0.314	1.1	2.4	2.17	0.26	2.17	0.188	0.119	0.135	0.584
Corner Brook Frequency Converter-60Hz	25	6	0.048	-	0.060	2.48	1.27	0.73	0.301	-	0.19	0.11	0.111	0.2862
Corner Brook Frequency Converter-50Hz	25	12.45	0.06	-	0.060	2.48	1.6	0.81	0.327	-	0.19	0.1045	0.1994	0.5814
Happy Valley GT- SynchronousCondenser Operation	26.57	10.7	0.05	3.2	0.050	1.7377	1.93	1.77	0.213	0.305	0.158	0.122	0.1843	0.6471

	Unit-MVA	Td0'	Td0"	Tq0"	H	Xd	Xq	Xd'	Xd"	Xl	S1.0	S1.2
		(s)	(s)	(s)	(kW-s/kVA)	(pu on Machine Rating)						
HYDRO UNITS												
Churchill Falls Unit A1/3/5/7/9	500	9.23	0.07	0.107	3.881	0.98	0.65	0.29	0.22	0.14	0.191	0.464
Churchill Falls Unit A2/4/6/8/10/11	500	8.0	0.071	0.25	3.807	1.00	0.62	0.28	0.22	0.14	0.191	0.464
Muskrat Falls G1/4	228.9	7.41	0.07	0.07	4.1	1.027	0.559	0.34	0.254	0.15	0.086	0.293
Bay D'Espoir Unit #1	85	6.24	0.065	0.08	5.24	1.3396	0.7497	0.3001	0.1802	0.132	0.1702	0.5621
Bay D'Espoir Unit #2	85	6.24	0.065	0.08	4.868	1.3396	0.7497	0.3001	0.1802	0.132	0.1233	0.5158
Bay D'Espoir Unit #3-6	85	6.24	0.065	0.08	5.24	1.3396	0.7497	0.3001	0.1802	0.132	0.1339	0.5504
Bay D'Espoir Unit #7	172	7.2	0.07	0.08	3.883	0.945	0.357	0.229	0.142	0.12	0.1364	0.4151
Cat Arm Unit #1/2	75.5	7.3	0.083	0.06	4.02	0.912	0.4427	0.254	0.181	0.1708	0.122	0.391
Granite Canal	45	5.8	0.042	0.042	4.0	0.711	0.48	0.21	0.23	0.1569	0.1651	0.577
Hinds Lake	83	8.24	0.035	0.17	6.6	1.2871	0.75	0.225	0.196	0.1287	0.1012	0.3529
Upper Salmon	88.4	4.345	0.04	0.06	3.5	0.86	0.594	0.3	0.215	0.12	0.084	0.3889
Paradise River	8.9	0.65	0.05	0.06	3.5	1.30	0.84	0.36	0.275	0.1	0.1189	0.3788
Deer Lake PowerCompany 60 HzUnits G1-G7	13.3	5.0	0.05	0.06	4.32	1.32	0.83	0.35	0.27745	0.2	0.11	0.48
NLP Rattling Brook Hydro Plant	15	5.0	0.05	0.06	2.5	0.9	0.54	0.23	0.16	0.100	0.11	0.48
NLP Sandy BrookHydro Plant	7	5.0	0.05	0.06	3.0	1.07	0.643	0.314	0.28	0.100	0.11	0.48
Abitibi-Consolidated - GrandFalls G4	27.5	7.37	0.035	0.035	2.96	1.545	0.7451	0.359	0.3506	0.1753	0.1905	0.4741
Abitibi-Consolidated - GrandFalls G5-8	5	5.0	0.05	0.05	5.5	1.243	0.932	0.435	0.3108	0.124	0.1	0.25
ACI-CHI Star Lake Hydro Plant	20.44	3.79	0.05	0.05	6.25	1.212	1.04	0.329	0.264	0.1	0.1356	0.525
NLP Rose BlancheBrook HydroPlant	7.63	3.5	0.035	0.04	3.28	1.26	0.76	0.332	0.199	0.1	0.0545	0.2121
Deer Lake Power50 Hz G8-9	24	5.0	0.05	0.06	2.917	1.25	0.83	0.35	0.4008	0.11	0.11	0.48
Deer Lake Power50 Hz Watson's Brook Unit#1/2	5.1	5.0	0.05	0.06	6.792	1.28	0.83	0.23	0.1499	0.2	0.11	0.48
Abitibi-Consolidated - BeetonUnit G9	33.3	3.8	0.032	0.032	1.827	0.98	0.56	0.41	0.29	0.28	0.2	0.75
Abitibi-Consolidated - Bishop's Falls Plant typical data	20	5.0	0.05	0.06	2.0	1.5	1.2	0.4	0.2	0.12	0.03	0.25
Rattle Brook- G1 Algonquin Power	4.02	3.14	0.039	0.062	1.052	1.399	0.775	0.306	0.186	0.107	0.156	0.276
Montagnais HQ Equivalent	30,000	-	-	-	3.6	-	-	0.22	-	-	-	-
Nova Scotia Equivalent	2,000	-	-	-	3.6	-	-	0.2	-	-	-	-

Table B-2: Generator Exciter Models

Model ID: EXST1

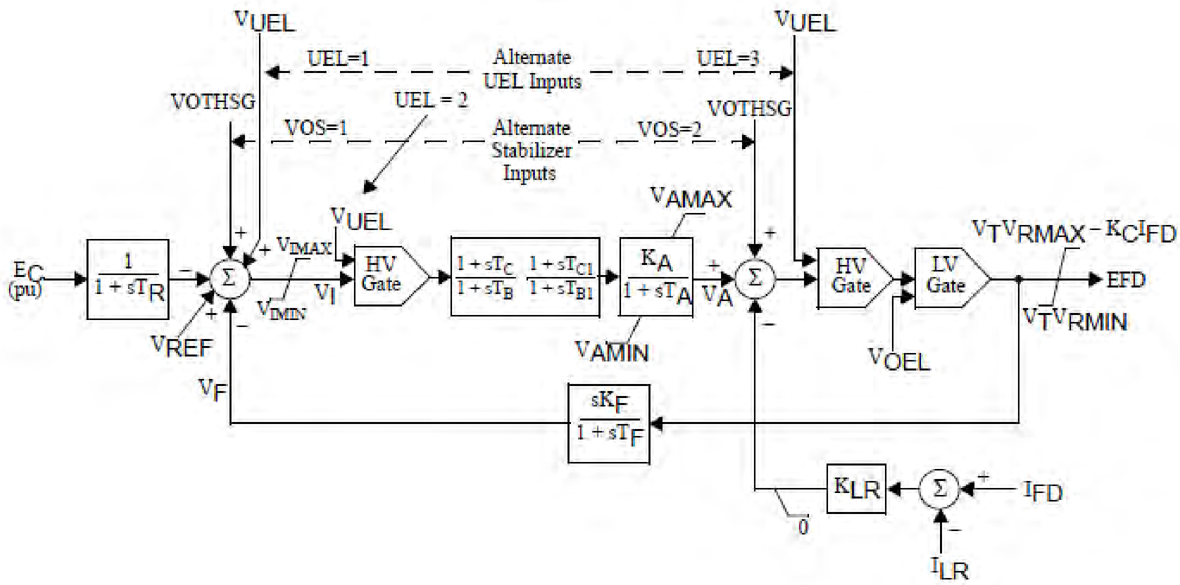


$V_S = VOTHSG + VUEL + VOEL$

Parameter	Churchill Falls	Muskrat Falls	HQ Equivalent	CB&P-G2	Grand Falls-G4
Tr	0.02	0.02		0	0
V_{Imax}	0.0262	0.0471		13.3	0.87
V_{Imin}	-0.027	-0.0476		-10.65	-0.87
Tc	0	0		1	0
Tb	0	0		1	0
Ka	400	400		200	90.676
Ta	0	0		0.001	0.02
Vrmax	7	12.3		13.3	7.5
Vrmin	-7.2	-12.7		-10.65	-0.1864
Kc	0	0		0	0.2
Kf	0	0		0	0.1609
Tf	1	1		1	1

Table B-3: Generator Exciter Models

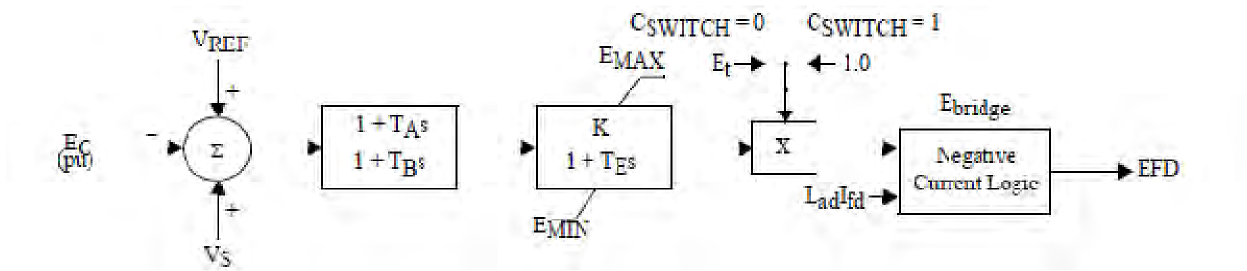
Model ID: ESST1A



Parameter	Bay d'Espoir						Cat Arm	Granite Canal
	G1	G2	G3	G4	G5	G6	G1	G1
Tr	0.02	0.02	0.02	0.02	0.02	0.02	0.0	0.0
V_{Imax}	3.6	3.4	3.5	3.48	4.13	4.16	6	6
V_{Imin}	-3.05	-2.88	-3	-2.95	-3.5	-3.52	-4.8	-4.8
Tc	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Tb	0.003	0.003	0.003	0.003	0.003	0.003	0.02	0.02
Tc1	2.5	2.5	2.5	2.5	2.5	2.5	2.59	1
Tb1	22.22	22.22	22.22	22.22	22.22	22.22	8.094	3.125
Ka	400	400	400	400	400	400	250	250
Ta	.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
V_{amax}	3.6	3.4	3.5	3.48	4.13	4.16	6	6
V_{amin}	-3.05	-2.88	-3	-2.95	-3.5	-3.52	-4.8	-4.8
V_{rmax}	3.6	3.4	3.5	3.48	4.13	4.16	6	6
V_{rmin}	-3.05	-2.88	-3	-2.95	-3.5	-3.52	-4.8	-4.8
Kc	0	0	0	0	0	0	0	0
Kf	0	0	0	0	0	0	0	0
Tf	1	1	1	1	1	1	1	1
K_{LR}	0	0	0	0	0	0	0	0
I_{LR}	0	0	0	0	0	0	0	0

Table B-3: Generator Exciter Models

Model ID: SCRX

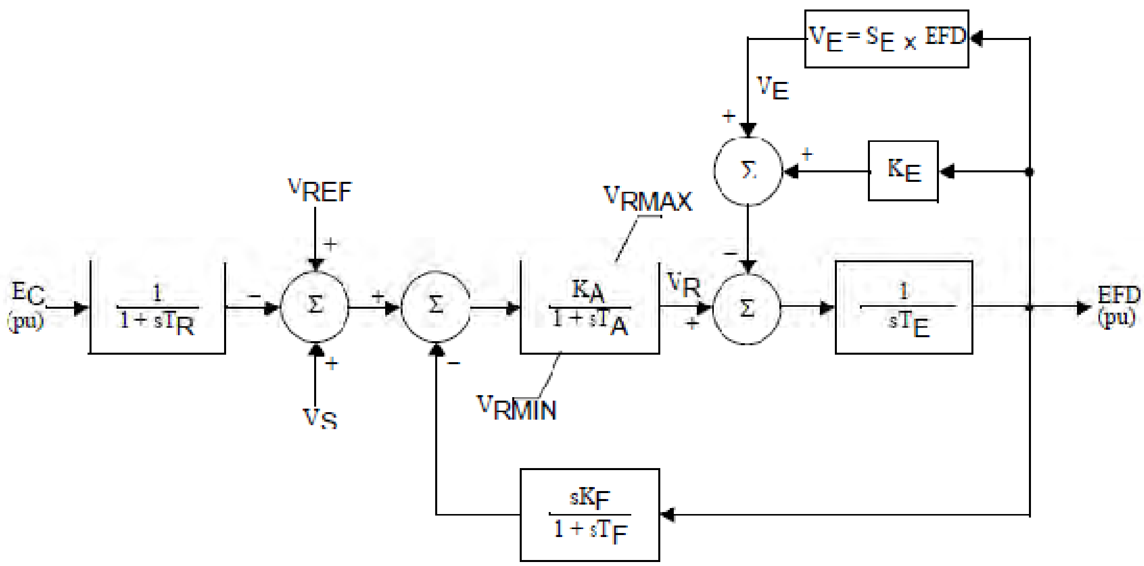


$V_S = VOTHSG + VUEL + VOEL$

Parameter	Bay d'Espoir G7	Holyrood G3	Hinds Lake G1	Upper Salmon G1	Grand Falls G5-8	CB&P Refiners -	Bishops Falls -
Ta/Tb	1	1	1	1	0.1	0.1	0.1
Tb	1	1	1	1	10	10	10
K	65	55	55	65	100	100	100
TE	0.035	0.035	0.035	0.035	0.05	0.05	0.05
Emin	-5.3	-6.32	-10.2	-4.48	0	0	0
Emax	6.1	7.32	11.7	5.56	2.5	5	2.5

Table B-3: Generator Exciter Models

Model ID: IEEET1



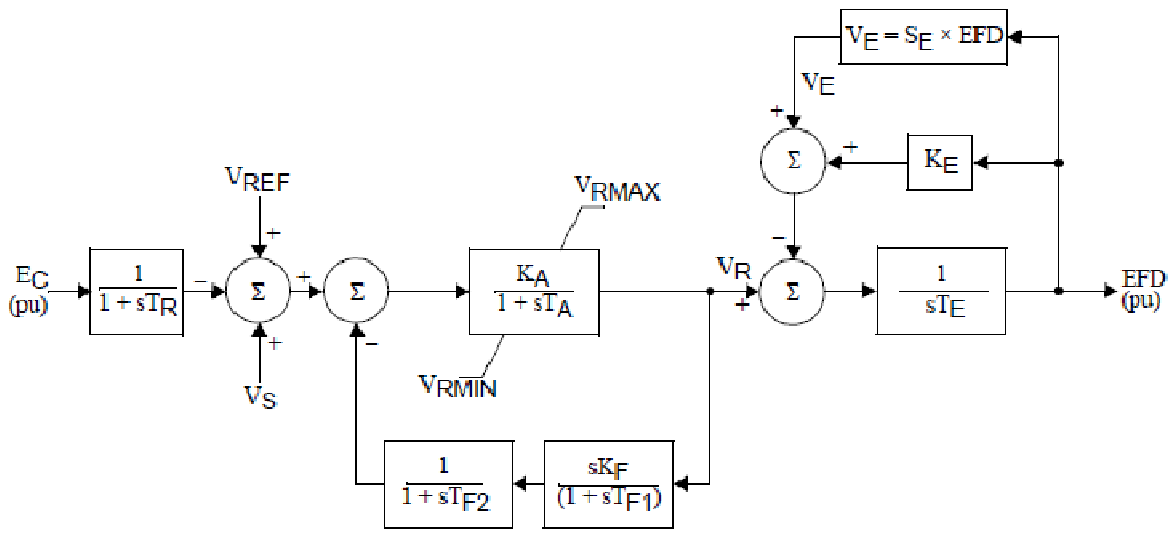
V_S = VOTHSG + VUEL + VOEL

Note: S_E is the saturation function

Parameter	Deer Lake G1-7
Tr	0
Ka	200
Ta	0.2
Vrmax	0
Vrmin	0
KE	0
TE	1
Kf	0.07
Tf	1
E1	3
S_{E1}	0.12
E2	4
S_{E2}	0.47

Table B-3: Generator Exciter Models

Model ID: IEEET2



$V_S = VOTHSG + VUEL + VOEL$

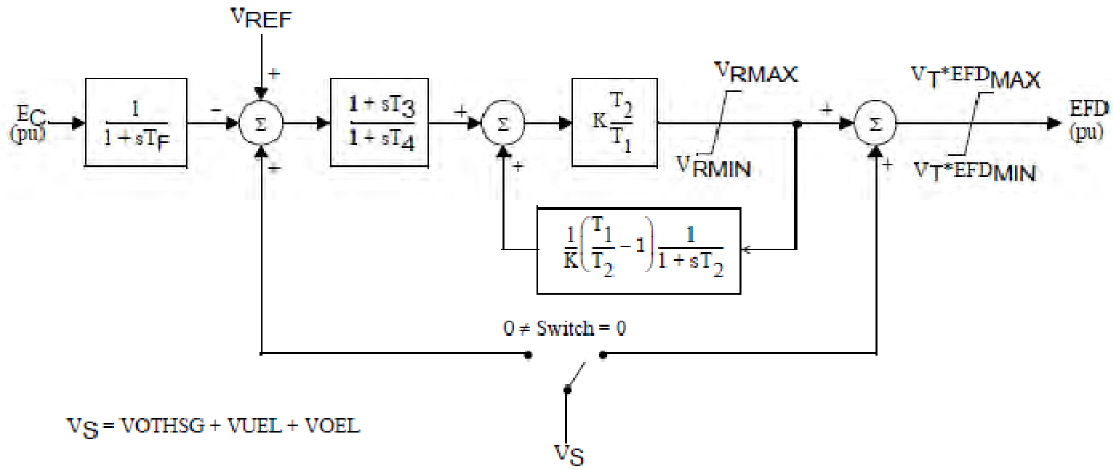
Note: S_E is the saturation function.

Parameter	Stephenville GT1-2	Hardwoods GT1-2	Paradise River G1
Tr	0.035	0.035	0.015
Ka	700	700	400
Ta	0.22	0.22	5
Vrmax	12.5	2.573	7.5
Vrmin	0	0	0
KE	1	1	0.57
TE	1	1	0.5
Kf	0.04	0.04	0.09
Tf1	0.6	0.6	0.32
Tf2	1	1	0.07
E1	5.64	2.698	3.72
S_{E1}	0.127	0.1781	0.0034
E2	6.767	3.9116	4.24
E2	0.448	0.3008	0.0126

SNC·LAVALIN	STABILITY STUDIES	Revision		Page
	Nalcor Doc. No. ILK -SN-CD-8000-EL-RP-0001-01	B2	Date	
	SLI Doc. No. 505573-480A-47ER-0004	01	06-Mar-2012	B-7

Table B-3: Generator Exciter Models

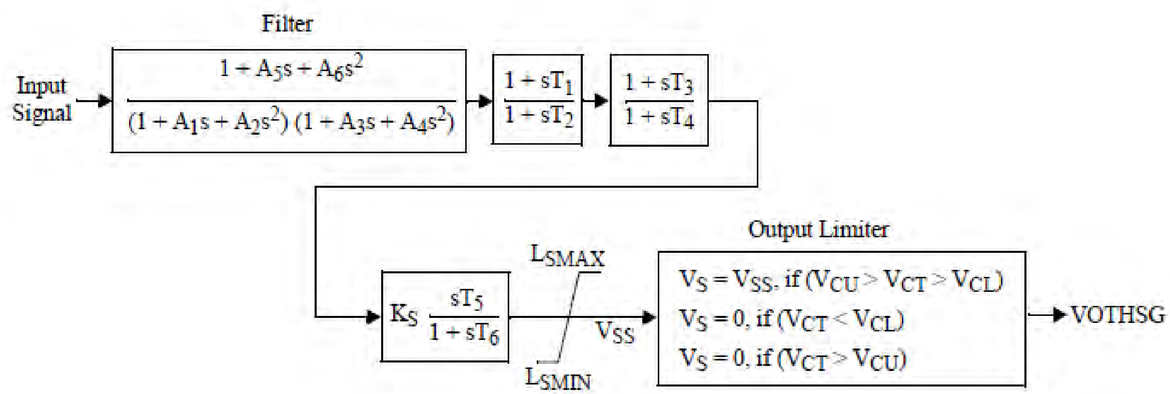
Model ID: BBSEX1



Parameter	Cat Arm G2
TF	0.035
T3	1.0
T4	3.91
T1	0.1
T2	0.035
K	70
Vrmax	8
Vrmin	-8
Efdmax	8
Efdmin	-6.4

Table B-4: Supplementary Stabilizer Models

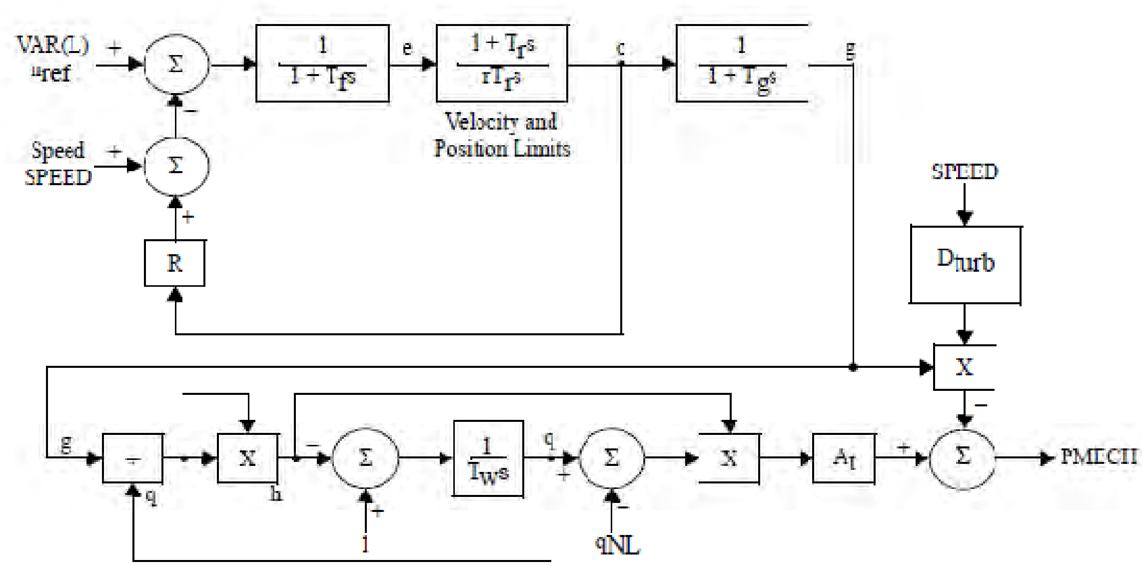
Model ID: IEEEST



Parameter	Churchill Falls G1-11	Muskrat Falls G1-4
A1	0	0
A2	0	0
A3	0	0
A4	0	0
A5	0	0
A6	0	0
T1	0	0
T2	1	1
T3	0.1	0.1
T4	1	1
T5	1	1
T6	0.08	0.08
Ks	3.5	3.5
Lsmax	0.1	0.1
Lsmin	-0.15	-0.15
Vcu	0	0
Vcl	0	0

Table B-5: Speed Governor Models

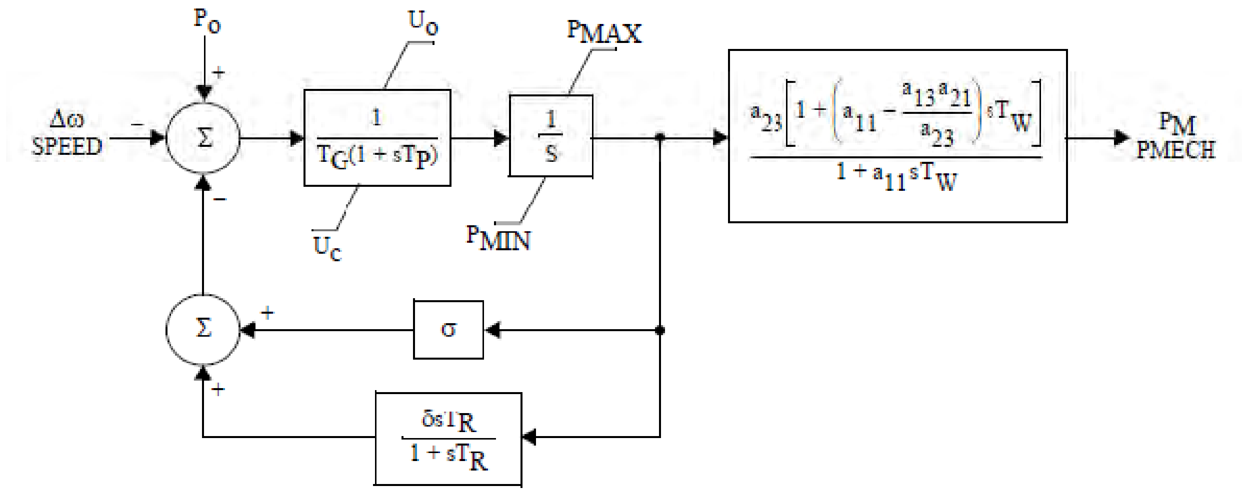
Model ID: HYGOV



Parameter	Muskrat Falls	Deer Lake	Bay d'Espoir						
	G1-4	G1-7	G1	G2	G3	G4	G5	G6	G7
R	0.05	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.01
r	0.44	0.5	0.44	0.35	0.26	0.41	0.34	0.34	0.4
Tr	4.88	6	14	8	12.5	14	12.5	8.25	17
Tf	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Tg	0.5	0.5	0.5	0.5	0.3	0.5	0.3	0.3	0.5
VELM	0.094	0.134	0.082	0.082	0.089	0.089	0.089	0.089	0.095
Gmax	0.945	0.79	0.835	0.835	0.892	0.892	0.892	0.892	0.947
Gmin	0	0.79	0	0	0	0	0	0	0
Tw	1.22	2	2.14	2.14	2.17	2.17	2.27	2.27	3.6
At	1.04	1.2	1.2	1.2	1.087	1.2	1.087	1.087	1.087
Dturb	0	0	0	0	0.75	0	3.5	1.25	1.15
Qnl	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.075

Table B-5: Speed Governor Models

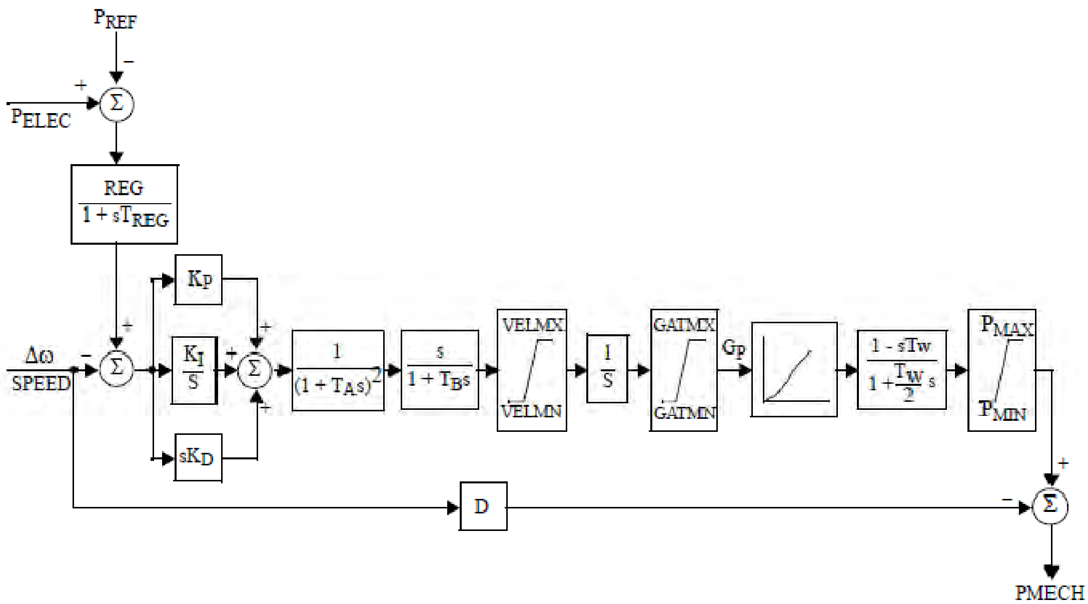
Model ID: IEEEG3



Parameter	Churchill Falls G1-11
Tg	0.3
Tp	0.04
Uo	.01
Uc	-0.1
Pmax	1
Pmin	0
σ	0.05
δ	0.293
Tr	5.5
Tw	1.1
a1	0.5
a2	1
a3	1.5
a4	1

Table B-5: Speed Governor Models

Model ID: WPIDHY

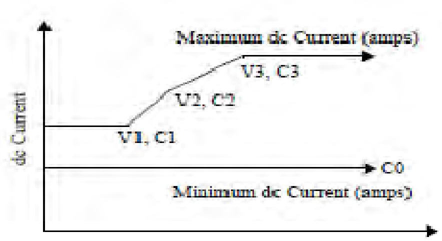


Parameter	Paradise River G1		
Treg	1.8	G0	0.15
REG	0.05	G1	0.5
Kp	1	P1	0.4118
Ki	1	G2	0.75
Kd	0	P2	0.7059
Ta	0.035	P3	1
Tb	0.035		
VELmax	0.1303		
VELmin	-0.1215		
GATmax	0.9647		
GATmin	0		
Tw	1.35		
Pmax	1		
Pmin	0		
D	0		

Table B-5: HVdc Converter Model

Model ID: CDC4T

Parameter	Units	Island Link	Maritime Link
ALFDY-Min. Alpha	deg	5	5
GAMDY-Min. Gamma	deg	18	18
TVDC-dc Voltage Transducer Time Constant	s	0.01	0.01
TIDC-dc Current Transducer Time Constant	s	0.01	0.01
VBLOCK-Rectifier ac Blocking Voltage	pu	0.6	0.6
VUNBL Rectifier ac Unblocking Voltage	pu	0.65	0.65
TBLOCK-Min. Blocking Time	S	0.1	20
VBYPAS-Inverter dc Bypassing Voltage	kV	235	0.6
VUNBY-Inverter ac Un-bypassing Voltage	pu	0.95	0.65
TBPAS-Min. Bypassing Time	s	0.1	0.1
RSVOLT-Min. dc Voltage following Block	kV	10	10
RSCUR-Min. dc Current following Block	A	10	10
VRAMP-Voltage Recovery Rate	pu/s	10	10
CRAMP-Current Recovery Rate	pu/s	10	10
C0-Min. Current Demand	A	150	0
V1-VDCOL Set Point	kV	100	60
C1-VDCOL Set Point	A	386	375
V2-VDCOL Set Point	kV	240	100
C2-VDCOL Set Point	A	2,580	1,300
V3-VDCOL Set Point	kV	320	200
C3-VDCOL Set Point	A	2,580	1,300
TCMODE-Min Time in Switched Mode	s	0.1	0.1



Voltage-Dependent Upper Current Limit

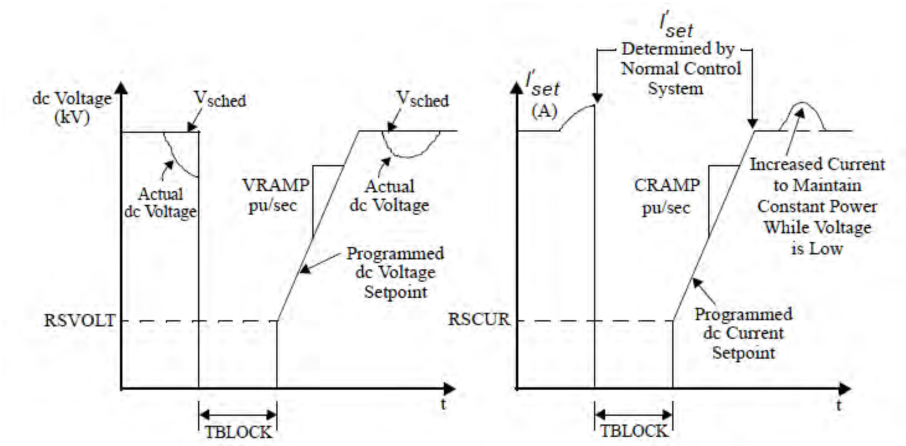
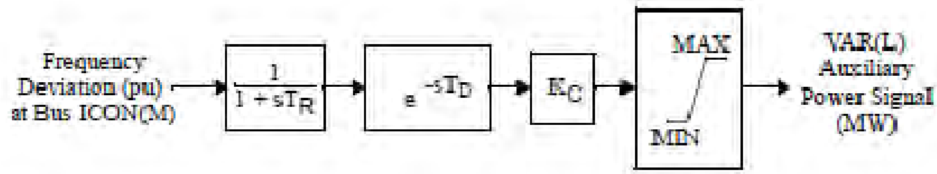

dc Voltage (kV)
Vsched
Actual dc Voltage
VRAMP pu/sec
Vsched
Actual dc Voltage
Programmed dc Voltage Setpoint
RSVOLT
TBLOCK
t
I'set
Determined by Normal Control System
I'set (A)
CRAMP pu/sec
Increased Current to Maintain Constant Power While Voltage is Low
RSCUR
Programmed dc Current Setpoint
TBLOCK
t

Table B-6: HVdc Frequency Control Model

Model ID: PAUX1

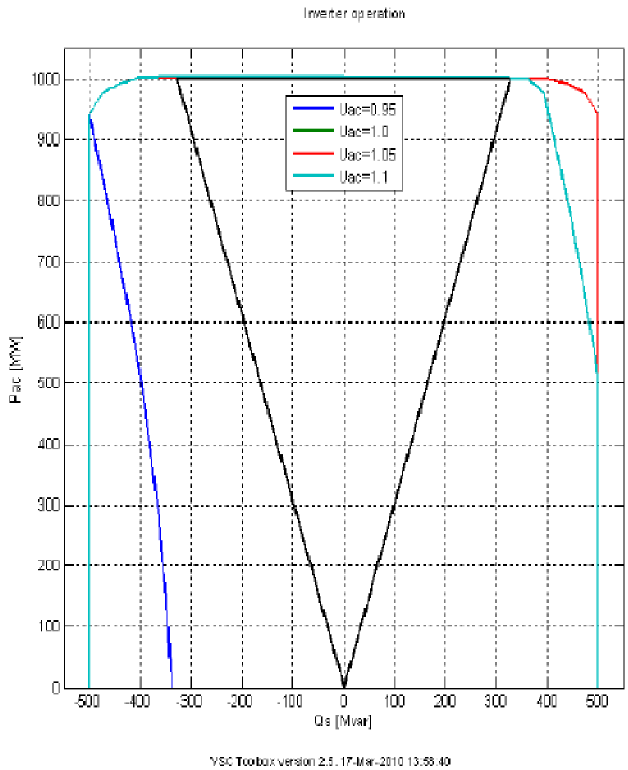


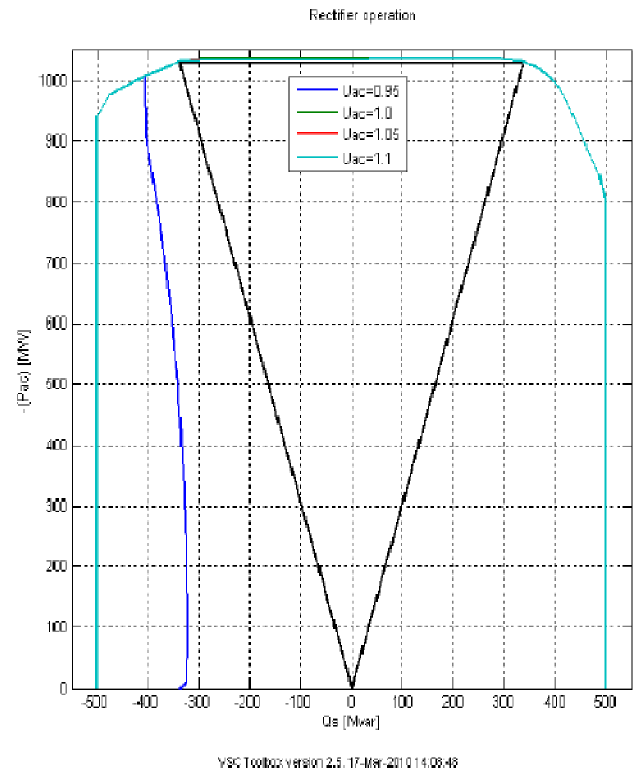
Parameter	Units	Soldiers Pond	Bottom Brook
Tr	s	0.05	0.05
TD	s	0	0
Kc	pu	-55,000	75,000
MAX	MW	10,000	0
MIN	MW	-1,050	-2,000

APPENDIX C

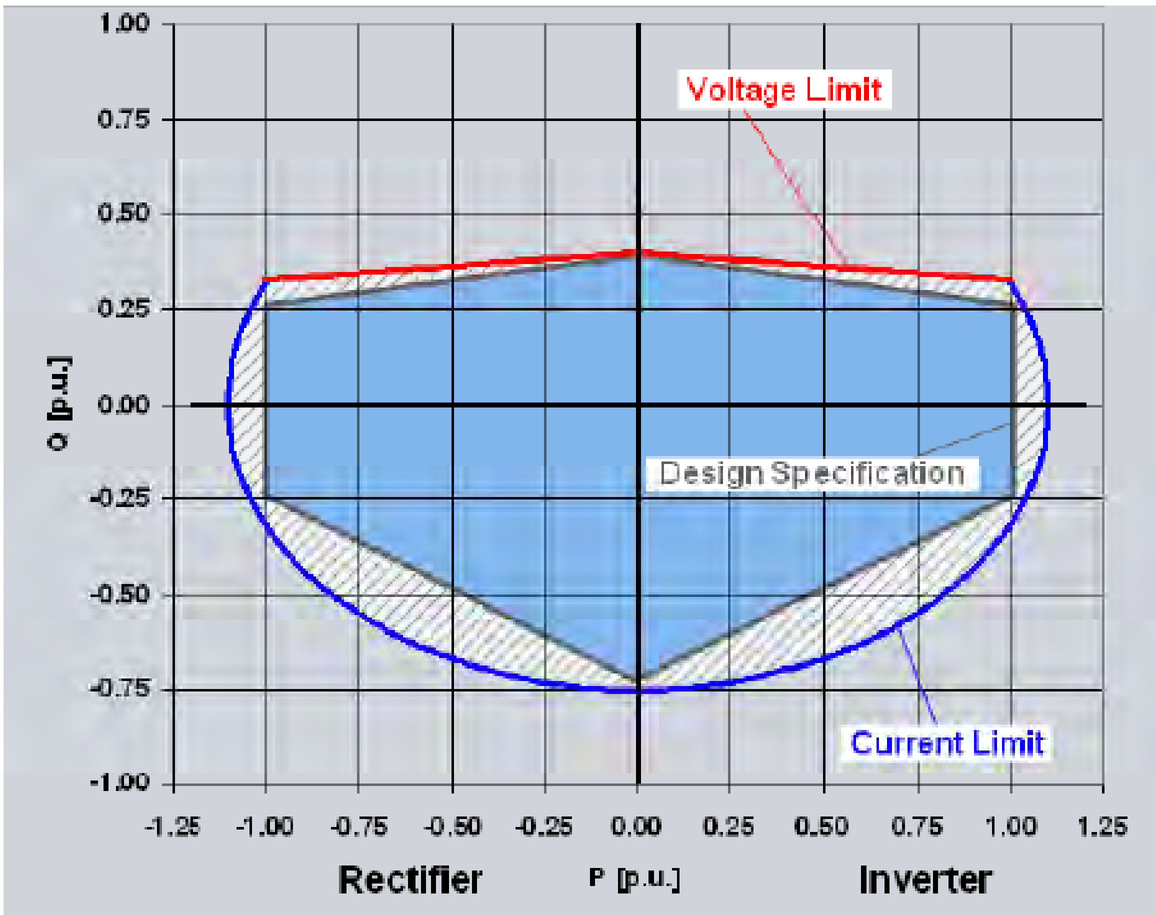
PQ CURVES OF TYPICAL VSC

PQ-Curve from ABB





PQ-Curve from Siemens



SNC·LAVALIN

nalcor energy

Lower Churchill Project

HARMONIC IMPEDANCE STUDIES

SLI Document No.: 505573-480A-47ER-0007-00

Nalcor Reference No.: ILK-SN-CD-8000-EL-SY-0002-01-B1

Date: 06-March 2012

Prepared by: M Ch
Mohamed El Chehaly

Verified by: PAnderson
Peter Anderson

Approved by: Satish Sud
Satish Sud

REGISTERED PROFESSIONAL ENGINEER
PEG Newfoundland and Labrador
SATISH SUD
Satish Sud
SIGNATURE
6 - MAR-2012
DATE
NEWFOUNDLAND & LABRADOR

Revision					Remarks
N°	By	Verif.	Appr.	Date	
00	MEC	PCA	SS	06-Mar-2012	Issued for Acceptance

TABLE OF CONTENTS

Page No.

List of Figures

List of Tables

Appendices

1 INTRODUCTION

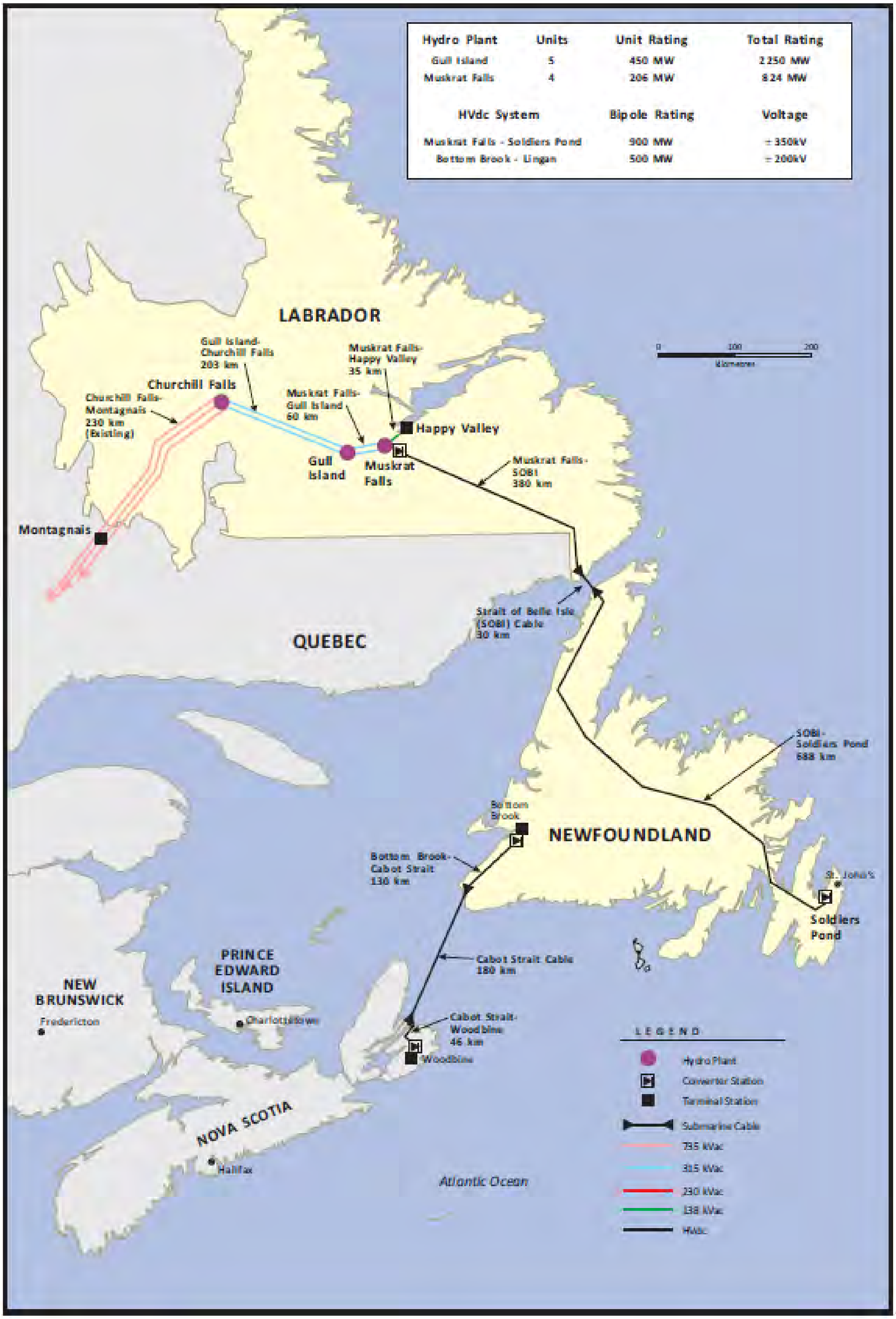
1.1 Overview of the System

This Report presents the results of the harmonic impedance studies carried out to determine the range of harmonic impedances presented by the ac systems at the terminals of the HVdc interconnection between Muskrat Falls and Soldiers Pond (Island Link). The converter station at Bottom Brook and the Nova Scotia power system (Maritime Link) were not considered in this study.

Figure 1-1 provides an overview of the areas considered in these studies. The connection to the Trans-Energie 735 kV system in Quebec was represented by a simple equivalent at the Montagnais substation. The Emera system in Nova Scotia was represented by a simple equivalent at the inverter station of the Maritime Link. The ac system between Churchill Falls and Muskrat Falls and the on-island ac system (shown in Figure 1-2) were modelled in detail. Since the objective of these studies was to determine the harmonic impedances of the ac systems at each converter station of the Island Link, the HVdc connections were not included in the system model, along with any harmonic filters that may be connected as part of the converter station design.

Starting from the base case scenarios provided by Nalcor, the present studies are designed to determine the range of harmonic impedances that will occur under different operating scenarios (ranging from peak load to extreme light load) for both normal and outage conditions.

Figure 1-1: Project Area Map



SNC·LAVALIN	HARMONIC IMPEDANCE STUDIES	Revision		
	Nalcor Doc. No. ILK-SN-CD-8000-EL-SY-0002-01	B1	Date	Page
	SLI Doc. No. 505573-480A-47ER-0007	00	06-Mar-2012	3

Figure 1-2: Provincial Transmission Grid

1.2 Objectives of the Studies

The harmonic impedance studies were designed to achieve the following objectives:

- To develop a harmonic impedance model of the interconnected systems of Newfoundland and Labrador with interconnections into Quebec and Nova Scotia,

- To analyze a wide range of operating scenarios for the initial year of operation of the Island Link (2017-18) under both system normal and single contingency outage conditions,

- To formulate a range of impedances for the ac systems at Muskrat Falls and Soldiers Pond converter stations at each harmonic frequency.

These harmonic impedance ranges will be suitable for potential suppliers to carry out an initial design of the harmonic filtering equipment at each converter station for the purpose of preparing a bid. Before the detailed design of these filters is undertaken, the selected contractor should be required to repeat these studies using the latest information from Nalcor concerning the ac system configuration and operating scenarios.

2 STUDY BASIS

NALCOR provided nineteen base case scenarios for examination. These scenarios are presented in Table 2-1. These scenarios were reduced to eleven operating scenarios by removing those scenarios that involved changes to only the HVdc systems or changes to the ac system that will not affect the ac system impedance. The eliminated scenarios were BC-14, BC-15, BC-16 and BC-17 which involved dc outages; BC-4 which considered the 2041 peak load, but with the same ac system and generation as in 2017 and since only the load has changed this will have little effect on the harmonic impedances; and BC-1, BC-2 and BC-3 which are identical to BC18, BC-19 except for the number of units connected at Muskrat Falls. These differences were accounted for in the outage cases considered for BC-18 and BC-19.

The major additions to the existing (2011) system planned by Nalcor consist of:

- A new 230 kV line from Granite Canal to Bottom Brook to strengthen the supply to Bottom Brook and the Western region,
- A new 230 kV line from Bay d'Espoir to Western Avalon.

Following the conclusions derived from the *Load Flow and Short-circuit Studies* (Nalcor MFA-SN-CD-3540-EL-SY-0001-01/ SLI 505573-480A-47ER-0003) and the *Stability Studies* ((Nalcor LCP-SN-CD-8000-EL-RP-0001-01/ SLI 505573-480A-47ER-0004), 2x150 MVAr high-inertia synchronous condensers were considered to be connected at the Soldiers Pond 230 kV bus via suitable step-down transformers. The above studies also showed a requirement for either a static var compensator (SVC) at the Bottom Brook converter station or the use of VSC technology for the converter itself. For the harmonic impedance studies, the SVC used in the load flow and stability studies was represented as a fixed shunt element. Since the Bottom Brook converter is electrically remote from the Soldiers Pond converter, the impact of this will not be significant.

Table 2-1: Base Case Scenarios

No.	NLH System Load	NS Export Bottom Brook	Island Import Muskrat Falls/Soldiers Pond	Island Generation	Comments
BC-1	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 3-units @ Muskrat Falls
BC-2	Peak-2017(1552MW)	239MW	900/814MW	Maximum	Winter Peak 3-units @ Muskrat Falls
BC-3	Peak-2017(1552MW)	158MW	798/730MW	Maximum	Winter Peak
BC-4	Peak-2041(1900MW)	0MW	900/814MW	Maximum	Winter Peak
BC-5	Intermediate-2017(1100MW)	158MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-6	Intermediate-2017(1100MW)	158MW	276/268	Maximum	Spring/Fall day
BC-7	Intermediate-2017 (1100MW)	500MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-8	Light (700MW)	158MW	414/400MW	Minimum	Summer day
BC-9	Light (700MW)	158MW	81/80MW	Economic Dispatch	Summer day
BC-10	Light (700MW)	500MW	900/814MW	Economic Dispatch	Summer day
BC-11	Extreme Light (420MW)	0MW	81/80MW	Economic Dispatch	Summer night
BC-12	Extreme Light (420MW)	320MW	81/80MW	Economic Dispatch	Summer night
BC-13	Extreme Light (420MW)	320MW	457/435MW	Minimum	Summer night
BC-14	Peak-2017 (1552MW)	-260MW	286/260MW-Monopole	Maximum	Winter Peak
BC-15	Intermediate-2017(1100MW)	158MW	378/333MW-Monopole	Economic Dispatch	Spring/Fall day
BC-16	Light (700MW)	500MW	638/518MW-Monopole	Minimum	Summer day
BC-17	Extreme Light (420MW)	0MW	215/200MW-Monopole	Minimum	Summer night
BC-18	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls
BC-19	Intermediate-2017(1100MW)	500MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls

Table 2-2: Generation Dispatch Levels

	Unit Size		BC1	BC2	BC3	BC4	BC5	BC6	BC7	BC8	BC9	BC10	BC11	BC12	BC13	BC14	BC15	BC16	BC17	BC18	BC19
	MW	MVA																			
NLH System Load (MW)			1552	1552	1552	1900	1100	1100	1100	700	700	700	420	420	420	1552	1100	700	420	1552	1100
HVDC Export BBK (MW)			158	239	158	0	158	158	500	158	158	500	0	320	320	-260	158	500	0	158	500
Generation Dispatch																					
Churchill Falls Plant	6050	6722	4219	4229	4199	5031	5465	4357	4706	2707	2041	2963	2794	3330	2959	4205	4505	3330	2794	4219	4706
Muskrat Falls Plant	824	916	602	613	618	618	757	618	618	735	824	824	378	415	476	574	618	415	378	824	824
HVDC at Soldiers Pond			815	815	730	815	815	268.5	815	400	80	815	80	80	435	260	333	518	200	815	815
NLH - Hydro																					
Bay d'Espoir Unit 1	76.5	85	70	75	75	75	68	75	65	67	60.5	65.7	67	66	off	75	72	60	61	70	65
Bay d'Espoir Unit 2	76.5	85	70	75	75	75	off	75	65	off	60.5	off	off	66	66	75	72	off	off	70	65
Bay d'Espoir Unit 3	76.5	85	70	75	75	75	68	75	65	67	60.5	65.7	67	66	off	75	72	60	61	70	65
Bay d'Espoir Unit 4	76.5	85	70	75	75	75	off	75	65	off	60.5	off	off	66	off	75	72	60	off	70	65
Bay d'Espoir Unit 5	76.5	85	70	75	75	75	68	75	65	off	60.5	65.7	off	66	off	75	72	60	off	70	65
Bay d'Espoir Unit 6	76.5	85	70	75	75	75	off	75	65	off	60.5	65.7	off	66	off	75	72	60	off	70	65
Bay d'Espoir Unit 7	155	172	145	154	154	154	off	154	135	135	135	off	sc	off	135	154	150	124	sc	145	135
Cat Arm Unit 1	68	75.5	50	65	65	65	sc	65	35	36	36	36	46	39	36	63.5	54	36	36	50	35
Cat Arm Unit 2	68	75.5	50	65	65	65	sc	65	35	sc	36	sc	off	off	off	63.5	54	36	off	50	35
Upper Salmon	84	88.4	78	84	84	84	75	84	71	75	70	70	75	75	off	84	75	70	off	78	71
Hinds Lake	75	83	70	75	75	75	69	75	67	off	67	off	off	69	off	75	69	67	off	70	67
Granite Canal	40.5	45	32	40	40	40	28	40	27	27	27	27	27	30	27	32	28	27	off	32	27
Paradise River	9	10	8	8	8	8	7	8	7	off	7	7	off	7	off	8	7	7	off	8	7
NLH - Thermal																					
Soldiers Pond	-	300	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc
Hardwoods GT1/2	57	63.5	sc	sc	sc	45	sc	sc	sc	sc	sc	sc	sc	sc	sc	50	sc	sc	sc	sc	sc
Stephenville GT1	57	63.5	off	off	off	25	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Holyrood Unit 1	175	194.4	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Holyrood Unit 2	175	194.4	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc
Holyrood Unit 3	159	177.2	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc	sc
Holyrood CT1	16	17.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Holyrood CT2	16	17.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NUGS																					
Star Lake			17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4
Rattle Brook			3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
CBP&P			18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Exploits			76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76	76
Wind																					
St. Lawrence			off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Fermeuse			off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off	off
Total Generation			1783	1871	1786	1986	1313	1325	1697	922	936	1333	477	811	814	1405	1317	1300	473	1783	1697

2.1 System Models

In terms of system modeling, the ac system was represented by conventional models common to both steady-state and stability studies. This data was provided by Nalcor in the form of PSS®E data files. This data was converted into the format required by the PSAF-HARMO® software used for the harmonic impedance calculations. In general, the harmonic models used in this software are based on the recommendations of CIGRE, IEEE and IEC. A brief description of the models used is given below.

At each frequency, specified by the user, the impedance of each element of the system is calculated and then the Thevenin equivalent impedance is calculated at the bus of interest. This is carried out for each base case and all the contingency outage cases specified.

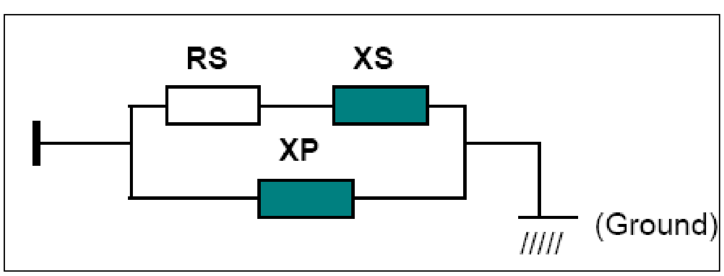
2.1.1 Generator Model

Generators were represented by their X_d'' (sub-transient, d-axis reactance) values as recommended by IEC Working Group CC02. For each harmonic, the fundamental value is simply multiplied by the harmonic order. All generators were represented with zero resistance.

The data for each generating unit is shown in Appendix B.

2.1.2 Load Model

The detailed CIGRE recommendations have been used for load models as shown in the figure below.



Where

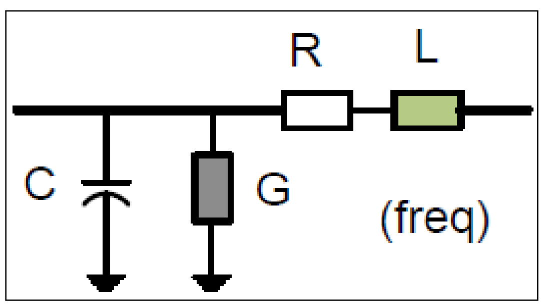
$$RS = V^2 / P$$
$$XS = A * h * RS$$
$$XP = h * RS / \left[(B * Q / P) - C\right]$$

P and Q are the fundamental real and reactive power of the load; *h* is the harmonic order; and *A*, *B* and *C* are constants provided from the CIGRE standard database.

2.1.3 Line Model

A distributed model with skin effect was used for the line model as provided in the PSAF-Harmo software. This model is represented by a series resistance and inductance, a shunt capacitance, and the conductance of the line as shown in Figure 2-1 below.

Figure 2-1: Distributed Parameter PSAF-Harmo Line Model



To include skin effect, the resistance is set up to increase with frequency as follows:

R(h) = R x g(h)

Where g(h) is an approximate fit to a curve given by:

$g(h) = 0.938 + 0.035\ \lambda^2$ for $\lambda < 2.4$,

$g(h) = 0.3 + 0.35\ \lambda$ for $\lambda \geq 2.4$,

Where $\lambda = 0.3883\ \sqrt{[f_0/60]}\ \sqrt{[h/R]}$ and h=harmonic order.

This model is valid for harmonic orders of 5 and above.

2.1.4 Shunt Capacitors and Reactors

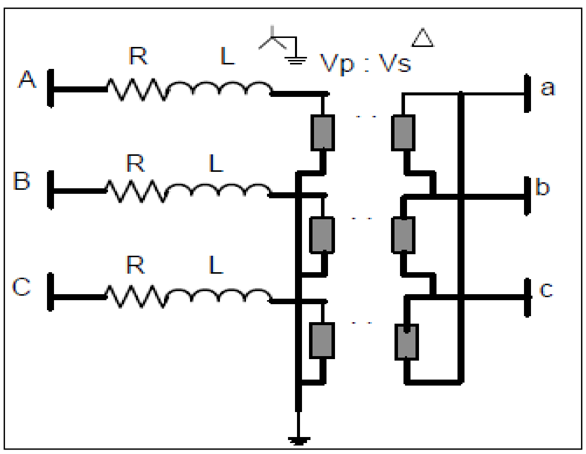
The harmonic impedance of shunt capacitors was modeled directly according to *Z(f)=1/(jωC)*. The internal losses of the capacitor were not modeled in this analysis.

Shunt reactors were modeled directly as series R-L circuits.

2.1.5 Two Winding Transformers

The two winding transformers were represented by the model provided in the PSAF-Harmo software: ideal transformers connected in series with a frequency dependent resistance R and inductance L derived directly from the transformer parameters, as shown in Figure 2-2 below.

Figure 2-2: Two Winding Transformer PSAF-Harmo Model

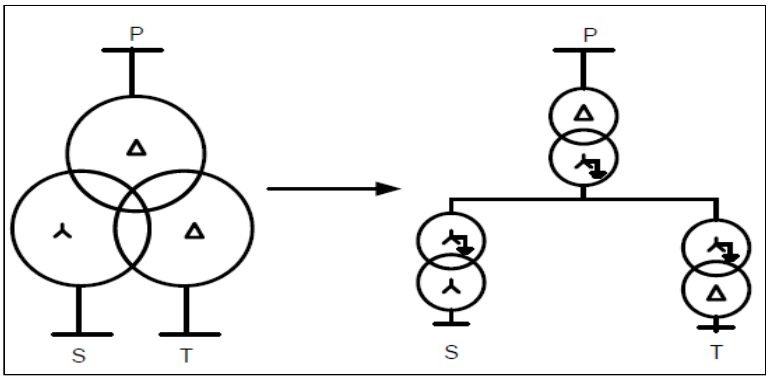


For three phase modelling, phase shifts of 0^0, $+30^0$ and -30^0 from primary to secondary are supported, according to the winding connections and phase shifts defined in the nameplate of each device.

2.1.6 Three Winding Transformers

Three-winding transformers were represented as three equivalent two winding transformers, as shown in Figure 2-3 below. Each two winding transformer was represented by the model shown in Figure 2-1 above.

Figure 2-3: Equivalent Representation of 3-Winding Transformers



3 RESULTS OF THE STUDIES

3.1 Compilation of Results

The scenarios were analyzed over the frequency range 60-3,000 Hz, i.e. up to the 50th harmonic, in steps of 1 Hz as normally required by converter manufacturers in order to determine the appropriate filter configuration. At each frequency the ac system impedance as seen at each converter bus was tabulated. This procedure was carried out for all the base case scenarios and for a range of outages on each base case. The outages considered the removal, in turn, of each element connected to the converter bus and then the removal of each element connected one bus away from the converter bus. In addition, outages of elements more remote from the converter bus were examined, but the results are only included where these outages had a measurable impact on the total impedance. For the Soldiers Pond converter, the high-inertia synchronous condenser was represented as 2x150 MVA units and the outage of one condenser was considered as one of the contingency cases. For Muskrat Falls, the outages also looked at a variation in the number of generating units connected at Muskrat Falls from four units down to zero units and in addition to the single-contingency outage of one of the 315 kV lines to Churchill Falls, the outage of both circuits to Churchill Falls was considered. The final selection of the synchronous condensers (number of units and unit rating) will have a significant impact on the harmonic impedance at Soldiers Pond as they are directly connected to the Soldiers Pond 230 kV bus.

These results were then compiled into a series of tables for each harmonic comprising the maximum and minimum system impedances from all the base cases and contingency outage cases. The values considered also covered a frequency variation of ±10% of each harmonic frequency. By considering the maximum magnitude with the maximum phase angle, the minimum magnitude with the minimum phase angle, the maximum magnitude with the minimum phase angle and the minimum magnitude with the maximum phase angle, an area can be defined within which all credible values of the system impedance will lie.

3.2 Results

The resulting values from all scenarios are shown in Table 3-1 for Soldiers Pond and Muskrat Falls. The results for each individual scenario are shown in Appendix A. It should be noted that the max/min values of the impedance magnitude are extracted independently of the max/min values of the impedance angle. This ensures that the max/min values for R and X are correctly captured. For illustrative purposes only, Figure 3-1 shows the resulting area bounded by the calculated impedance values on an R-X plot for the 11th and 13th harmonic for Soldiers Pond 230 kV. Figure 3-2 shows the corresponding plot for Muskrat Falls 315 kV. These plots are constructed using the following four segments for which the polar form of the impedances are converted into rectangular form for the R-X plot:

- Segment 1: Magnitude of Z_{max} kept constant, Phase angle varied between Θ_{max} and Θ_{min},
- Segment 2: Magnitude of Z_{min} kept constant, Phase angle varied between Θ_{max} and Θ_{min},
- Segment 3: Θ_{max} kept constant, Magnitude varied between Z_{max} and Z_{min},
- Segment 4: Θ_{min} kept constant, Magnitude varied between Z_{max} and Z_{min}.

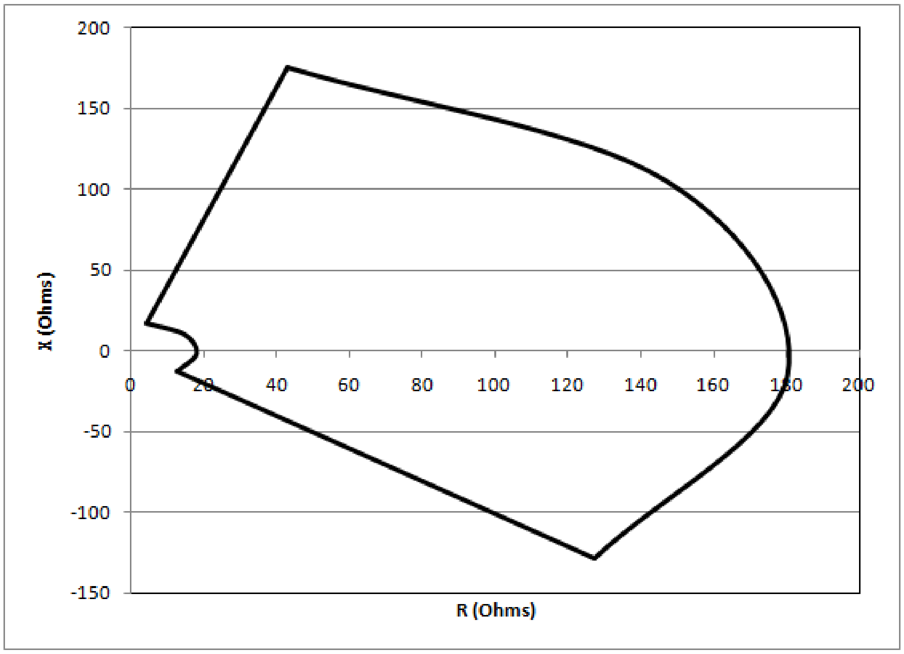
This information is considered suitable for use by potential converter manufacturers in the preliminary design of the harmonic filters.

Table 3-1: Max/Min AC System Impedances

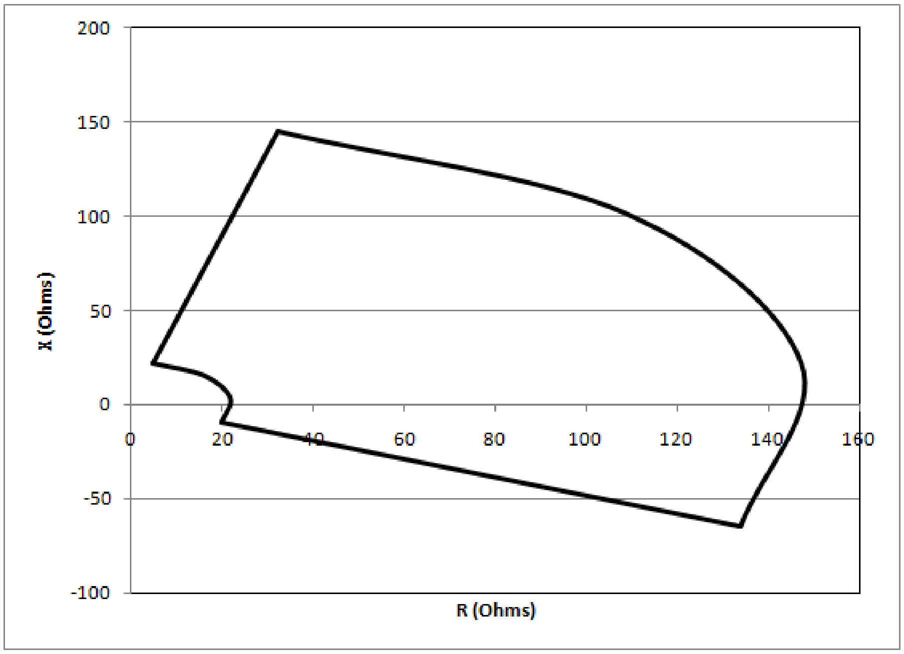
TERMINAL →	SOLDIERS POND				MUSKRAT FALLS			
Harmonic Order ↓	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max
2	23.1	63.8	45.4	77.8	48.7	72	238	79.6
3	33.9	31	70.7	72.9	29.6	-66.5	905	78.9
4	33.7	22.2	119	71.5	27.8	-55.2	907	78.7
5	30.8	14.4	120	69.4	45.8	-72.5	918	74.6
6	37.8	1.6	172	69.8	45.6	-81.6	918	70.3
7	53.2	-41.7	177	69.2	3.2	-83.6	708	81.9
8	31.3	-45.7	177	68.5	3.2	-83.6	621	84.8
9	17.8	-45.7	188	65.2	3.7	-79.9	840	85.7
10	17.8	-45.3	188	61.3	18.7	66	1226	85.7
11	17.9	-45.3	181	76.3	94.3	-67.5	2443	85.6
12	22.2	-41.1	167	76.8	40.8	-78.8	3379	84.2
13	22.2	-25.9	149	77.5	28.6	-84.8	3402	81.1
14	29.9	-4.9	248	79.2	28.6	-85.5	3402	73.5
15	48.5	-4.9	564	79.7	3.4	-85.5	3287	81.8
16	61	-61.6	937	79.7	3.4	-85.5	2670	84.6
17	30	-74.1	1034	79.7	3.4	-85.5	1999	86.4
18	17.8	-76.2	1034	79.7	3.4	-83.1	971	86.4
19	15.1	-76.2	1034	75.5	6.5	-80.4	434	86.4
20	14.8	-76.2	1034	71.6	8.2	-67.3	3761	86.4
21	14.8	-76.2	872	71.6	60.7	-85	3761	86.4
22	14.8	-74.5	872	71.6	49.2	-85.7	4068	86.1
23	14.8	-74	1056	72.2	5.9	-85.7	4068	84
24	15.5	-80.7	1056	72.2	3.9	-85.7	4068	85.6
25	31.6	-81.4	1294	72.2	3.9	-85.7	8729	87.1
26	28.5	-81.4	1294	72.2	3.9	-85.7	11409	87.3
27	28.5	-81.4	1294	72.2	3.9	-85.1	11409	87.3
28	28.5	-83.2	1294	71.1	3.9	-85.1	11409	87.3
29	28.5	-84.3	1294	64.9	3.9	-85.4	11409	87.3
30	28.5	-86.3	1294	57.4	7.3	-86.9	11409	87.3
31	39.7	-86.5	982	57.4	35.5	-87	11409	87.3
32	41.2	-86.5	982	51.9	3.8	-87	8861	87.2
33	23.5	-86.5	982	51.9	3.8	-87	8845	86.2
34	23.5	-86.7	692	19.3	3.8	-87	7252	87.2
35	22.9	-87.4	294	27.4	3.8	-87	7160	87.2
36	22.9	-87.4	259	27.4	3.8	-87	5397	87.2
37	9.8	-87.4	309	57.9	3.8	-87	6587	87.2
38	9.8	-87.4	351	57.9	3.8	-87.3	6587	87.2
39	5.6	-87.4	373	57.9	3.8	-87.5	6587	87.2
40	5.1	-87.4	409	64.2	8.8	-87.6	6587	87.2
41	5.1	-87.4	461	76	3.7	-87.8	6587	87.2
42	5.1	-87.4	477	76	3.7	-87.9	6587	87.3
43	5.1	-87	564	76	3.7	-87.9	6587	87.4
44	5.1	-87.7	564	76	3.7	-87.9	6587	87.4
45	5.1	-88.4	564	76	3.7	-87.9	6587	87.4
46	5.1	-88.4	564	76	3.7	-87.9	4119	87.4
47	5.1	-88.4	564	76	3.7	-87.9	4119	87.4
48	5.1	-88.4	564	76	3.7	-87.9	4119	87.4
49	8.7	-88.4	564	76	3.7	-87.9	6184	87.4
50	4.8	-88.4	564	73.8	3.8	-87.9	6184	87.4

Note: Zmin/max in ohms, Θmin/max in degrees

Figure 3-1: 11th/13th Harmonic Impedance Plot-Soldiers Pond 230 kV

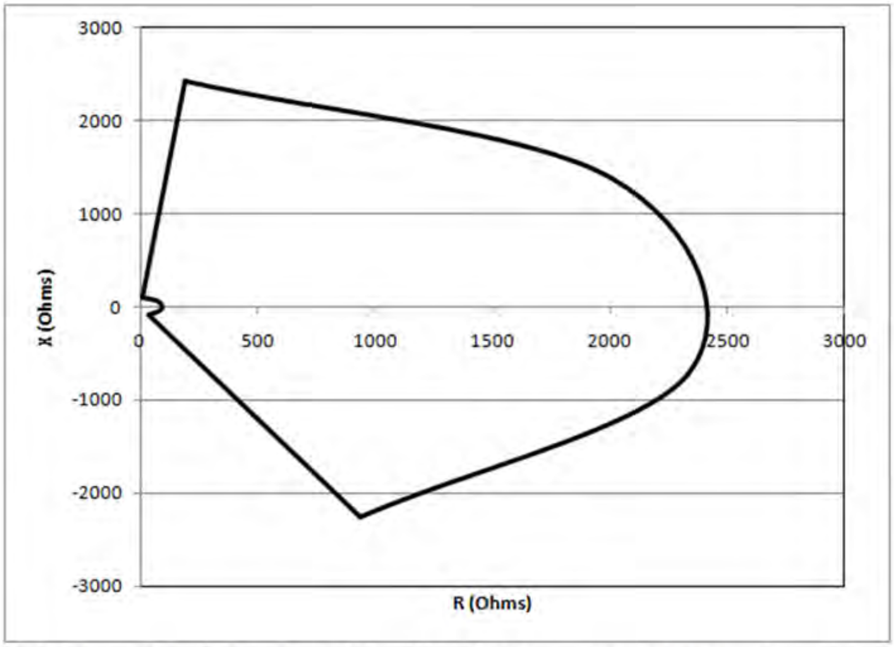


Z(min) =	17.9	Z(max) =	180.9	Theta (min) =	-45.3	Theta (max) =	76.3
Harmonic Order				11			

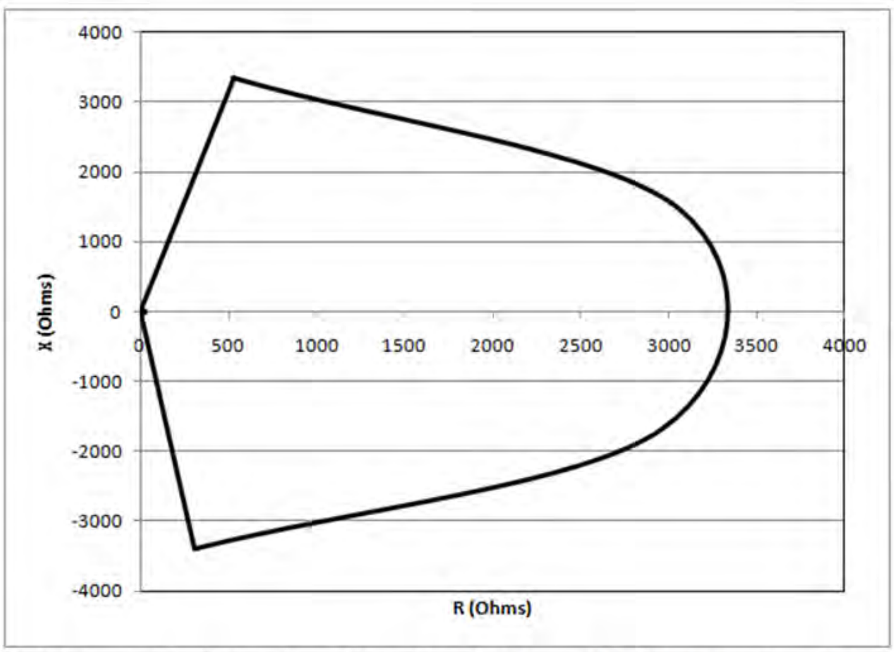


Z(min) =	22.2	Z(max) =	148.7	Theta (min) =	-25.9	Theta (max) =	77.5
Harmonic Order				13			

Figure 3-2: 11th/13th Harmonic Impedance Plot-Muskrat Falls 315 kV



Z(min) =	94.3	Z(max) =	2443.2	Theta (min) =	-67.5	Theta (max) =	85.6
Harmonic Order				11			



Z(min) =	28.6	Z(max) =	3401.9	Theta (min) =	-84.8	Theta (max) =	81.1
Harmonic Order				13			

APPENDIX-A
HARMONIC IMPEDANCE VALUES

Attachment A-1: Winter Peak and Spring/Fall Intermediate Scenarios
Attachment A-2: Summer Day/Light and Night/Extreme Light Scenarios

Attachment A-1: Scenarios

Scenario	Load	Island Link	Maritime Link	Island Dispatch
BC-18	Winter Peak 2017 1,552MW	814MW	158MW	Economic
BC-19	Intermediate 2017 1,100MW		500MW	
BC-5			158MW	
BC-6		268MW		Maximum
BC-7		814MW	500MW	Economic

SNC·LAVALIN	HARMONIC IMPEDANCE STUDIES	Revision		
	Nalcor Doc. No. ILK-SN-CD-8000-EL-SY-0002-01	B1	Date	Page
	SLI Doc. No. 505573-480A-47ER-0007	00	06-Mar-2012	A-2

Attachment A-1: Summary Results for Base Cases and Contingency Cases

Study Scenario →	BC 18				BC 19				BC 5				BC 6				BC 7			
Harmonic Order ↓	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max
2	23.1	63.8	33.1	70.2	24.1	67.5	36.3	73.5	24.7	64.7	37.7	72.6	23.9	67.6	36	73.4	24.1	67.5	36.3	73.5
3	33.9	45.3	46.1	66.2	37.3	39.8	53	68.7	35.9	36.8	48.8	66.1	36.9	40.8	52.5	68.9	37.3	39.9	53.1	68.7
4	38.1	36.1	52.3	60	38.5	30	61	59.9	36.3	33.3	59.3	61.2	38.9	30.6	60.2	59.9	38.6	30.1	60.9	59.8
5	31.3	35.5	65.4	66.5	31.5	30.4	72.2	67.3	32.6	33.8	67.7	67.9	31.6	30.8	71.9	67.3	31.6	30.4	72.3	67.3
6	37.8	39.5	75	69.4	41.9	34.2	89.4	68.8	43	36.7	88.5	69	41.5	34.7	88.2	68.9	41.9	34.3	89.3	68.8
7	53.2	37.8	97.2	69.2	59.2	30.8	112	67.8	59.7	34.3	111	67.6	58.7	32.1	111	68	59.2	30.8	112	67.9
8	64.5	28.8	114	68.5	60.8	7.4	121	65.7	68.2	8.7	120	65.8	61.7	9.2	119	66	60.8	7.5	121	65.8
9	65.2	10.5	137	65.2	59.7	-4	158	61.2	68.1	0.8	158	61.3	60.4	-3	157	61.5	59.7	-4	158	61.2
10	65.2	1.9	166	60.2	51.3	-4	163	52.4	50.3	-0.5	166	52.9	53	-3	163	53.3	51.4	-4	163	52.5
11	42.9	-3.5	167	49.9	35.1	-14	163	41.6	34.4	-14.5	166	41.1	35.4	-13.3	163	40.3	35.1	-14	163	41.5
12	42.8	-3.5	167	51.5	35.1	-14	156	61.3	34.4	-14.5	159	60.1	35.4	-13.3	158	60.9	35.1	-14	157	61.3
13	42.8	-3.5	149	56.8	35.1	-14	122	66.7	34.4	-14.5	114	67.8	35.4	-13.3	121	66.2	35.1	-14	122	66.7
14	55.1	8.6	214	66.5	47.1	9.1	227	73.6	46.6	8.8	228	73.3	47.2	9.4	225	73.2	47.2	9.1	226	73.5
15	69.5	8.6	403	69.2	61.9	6.9	446	75	61.3	7	441	74.8	63.1	7.1	439	74.7	61.9	6.9	446	75
16	73.6	-44.8	571	69.2	63.8	-53.2	693	75	66	-52.5	684	74.8	64.3	-52.5	685	74.7	63.8	-53.2	693	75
17	73.8	-67.5	606	69.2	74.7	-71.2	770	75	75.9	-71	765	74.8	76	-71	761	74.7	74.9	-71.2	769	75
18	19.9	-71	627	69.2	18.8	-73	770	74.9	19.2	-72.9	765	74.7	19	-72.9	761	74.6	18.8	-73	769	74.9
19	16.9	-71	627	70.8	16.2	-73	770	71.5	16.6	-72.9	765	70.9	16.3	-72.9	761	71.3	16.2	-73	769	71.4
20	16.4	-71	627	71.3	15.8	-73	770	71.6	16	-72.9	765	70.9	15.9	-72.9	761	71.5	15.8	-73	769	71.6
21	16.4	-71	697	71.3	15.8	-73	715	71.6	16	-72.9	693	70.9	15.9	-72.9	714	71.5	15.8	-73	716	71.6
22	16.4	-69.9	697	71.3	15.8	-70.7	715	71.6	16	-70.4	644	70.9	15.9	-70.7	714	71.5	15.8	-70.6	716	71.6
23	16.4	-67.1	790	72.2	15.8	-60.1	806	71.6	16	-61.4	839	70.9	15.9	-61	803	71.5	15.8	-60.2	806	71.6
24	16.4	-67.1	790	72.2	17.3	-67	806	69.7	17.2	-66.2	839	70	17.1	-65.9	803	69.8	17.3	-67	806	69.7
25	31.6	-67.1	1101	72.2	38.2	-69.4	1202	69.7	37.3	-68.3	1191	70	37.1	-68.3	1190	69.8	38.1	-69.4	1202	69.7
26	51.9	-67.1	1124	72.2	35.5	-69.4	1207	69.7	38.1	-68.3	1194	70	36.7	-68.3	1198	69.8	35.6	-69.4	1207	69.7
27	51.9	-79.4	1124	72.2	35.5	-79.8	1207	69.3	38.1	-80	1194	69.9	36.7	-79.7	1198	69.6	35.6	-79.8	1207	69.4
28	51.9	-83.1	1124	71.1	35.5	-83.2	1207	63.8	38.1	-83.2	1194	64.5	36.7	-83.2	1198	64.8	35.6	-83.2	1207	63.9
29	51.9	-84.3	1124	64.3	35.5	-83.6	1207	56.9	38.1	-83.7	1194	56.8	36.7	-83.7	1198	56.8	35.6	-83.6	1207	56.9
30	51.9	-84.5	1124	53.1	35.5	-85.5	1207	55.9	38.1	-85.4	1194	53.6	36.7	-85.4	1198	55.6	35.6	-85.4	1207	56.1
31	53	-85.7	879	53.1	39.8	-86.3	910	55.9	45	-86.2	916	53.6	40.4	-86.3	908	55.6	39.7	-86.3	908	56.1
32	54.8	-86.3	879	43.3	53.7	-86.3	910	44.8	50.5	-86.2	916	47.5	53.7	-86.3	908	45	53.7	-86.3	908	44.8
33	45	-86.3	879	43.3	31.7	-86.3	910	44.8	33.5	-86.2	916	47.3	32.1	-86.3	908	45	32.2	-86.3	908	44.8
34	43.5	-86.3	630	-25.1	31.6	-86.3	600	-10.2	33.5	-86.2	607	-13	31.9	-86.3	607	-11	32.1	-86.3	601	-11.1
35	24.3	-86.3	279	14.5	23.6	-87	269	16.3	24.8	-86.9	269	12.4	23.6	-86.9	270	16.3	23.6	-87	269	16.2
36	24.3	-86.3	185	14.5	23.6	-87	197	16.3	24.8	-86.9	196	12.4	23.6	-86.9	196	16.3	23.6	-87	196	16.2
37	16.6	-86.5	171	28.1	16.8	-87	177	35.6	16	-86.9	170	37	16.8	-86.9	177	35.4	16.8	-87	177	35
38	16.6	-86.5	206	28.1	16.6	-87	212	35.6	16	-86.9	218	37	16.7	-86.9	213	35.4	16.6	-87	211	35
39	7.4	-86.5	336	54.8	6.3	-87	359	56.4	6.5	-86.9	357	56.3	6.4	-86.9	355	56.3	6.4	-87	359	56.4
40	6.3	-86.5	385	54.8	5.8	-87	398	56.4	5.9	-86.9	396	60.2	5.9	-86.9	396	56.3	5.8	-87	398	56.4
41	6.3	-86.5	438	75.3	5.8	-87	436	75.5	5.9	-86.9	438	75.7	5.9	-86.9	435	75.5	5.8	-87	435	75.5
42	6.3	-86.5	477	75.3	5.8	-87	467	75.5	5.9	-86.9	470	75.7	5.9	-86.9	466	75.5	5.8	-87	467	75.5
43	6.3	-86.5	477	75.3	5.8	-86.7	467	75.5	5.9	-86.8	470	75.7	5.9	-86.7	466	75.5	5.8	-86.7	467	75.5
44	6.3	-86.7	477	75.3	5.8	-87.4	467	75.5	5.9	-87.3	470	75.7	5.9	-87.3	466	75.5	5.8	-87.4	467	75.5
45	6.3	-88.2	477	75.3	5.8	-88.3	467	75.5	5.9	-88.3	470	75.7	5.9	-88.3	466	75.5	5.8	-88.3	467	75.5
46	6.3	-88.3	477	75.3	5.8	-88.4	467	75.5	5.9	-88.4	470	75.7	5.9	-88.4	466	75.5	5.8	-88.4	467	75.5
47	6.3	-88.4	477	75.3	5.8	-88.4	467	75.5	5.9	-88.4	470	75.7	5.9	-88.4	466	75.5	5.8	-88.4	467	75.5
48	6.6	-88.4	477	75.3	6.7	-88.4	467	75.5	6.7	-88.4	470	75.7	6.7	-88.4	466	75.5	6.7	-88.4	467	75.5
49	9.2	-88.4	477	75.3	9.1	-88.4	467	75.5	8.9	-88.4	470	75.7	9.1	-88.4	466	75.5	9.1	-88.4	467	75.5
50	5.1	-88.4	477	71.9	5	-88.4	467	71.6	5	-88.4	470	71.5	5	-88.4	466	71.6	5	-88.4	467	71.6

Attachment A-2: Scenarios

<table>
<tr><th>Scenario</th><th>Load</th><th>Island Link</th><th>Maritime Link</th><th>Island Dispatch</th></tr>
<tr><td>BC-8</td><td rowspan="3">Light (Summer Day) 2017 700MW</td><td>400MW</td><td rowspan="2">158MW</td><td>Minimum</td></tr>
<tr><td>BC-9</td><td>80MW</td><td rowspan="4">Economic</td></tr>
<tr><td>BC-10</td><td>814MW</td><td>500MW</td></tr>
<tr><td>BC-11</td><td rowspan="3">Extreme Light (Summer Night) 2017 420MW</td><td rowspan="2">80MW</td><td>0MW</td></tr>
<tr><td>BC-12</td><td rowspan="2">320MW</td></tr>
<tr><td>BC-13</td><td>435MW</td><td>Minimum</td></tr>
</table>

SNC·LAVALIN	HARMONIC IMPEDANCE STUDIES	Revision		
	Nalcor Doc. No. ILK-SN-CD-8000-EL-SY-0002-01	B1	Date	Page
	SLI Doc. No. 505573-480A-47ER-0007	00	06-Mar-2012	A-4

Attachment A-2: Summary Results for Base Cases and Contingency Cases

Study Scenario →	BC 8				BC 9				BC 10				BC 11				BC 12				BC 13			
Harmonic Order ↓	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max	Zmin	θ min	Zmax	θ max
2	25.7	70	40.1	75.8	24.9	71.5	39.2	76.5	25.6	68.1	41.3	75.7	28.1	72.6	43.9	77.3	27.4	74.4	42.6	77.8	28.9	70.2	45.4	76.8
3	40.2	39.6	57.4	69	40.6	31	63.2	72.2	35.4	32	56.7	68.8	41.9	44	66.4	69.6	46.9	44.9	70.7	72.9	37.9	40.2	63.6	71.3
4	43.5	22.2	73.6	65.1	36.1	22.4	73.5	63.2	33.7	24.6	73.1	64.5	54	32.8	117	71	51.6	38.7	119	70.4	53.7	31.9	113	71.5
5	37	19.9	79.1	62.5	30.8	27.2	84.6	69.2	31.3	32.4	78.9	69.4	66.7	15.2	114	48.5	68.2	14.4	120	51.5	65.3	17.1	107	50.3
6	45.1	33.5	107	64.2	47.1	29.2	117	69.7	48.3	33.5	116	69.8	66.4	2.1	172	53.9	67.6	1.6	164	53.2	66.2	3.8	171	55.3
7	66.1	13.4	125	62.3	67.6	9.1	135	67.5	68.5	10.4	134	67.6	69.3	-41.5	172	53.3	69.8	-41.7	171	48.8	70.1	-41.6	177	54.9
8	58.2	-10.7	136	56.8	51	-19.8	158	62.8	59.2	-18.7	157	62.9	31.8	-45.4	171	34.4	31.3	-45.7	171	34.7	32.7	-44.5	177	34.1
9	45	-16.2	174	55.9	41.8	-22	188	58	44.9	-20.1	188	58.2	17.9	-45.4	170	50	17.8	-45.7	164	50.4	18.2	-44.5	175	48.5
10	32	-21.2	174	51	32.6	-24.4	188	49.4	32.1	-24.4	188	48.7	17.9	-45.3	170	60.9	17.8	-44.6	164	61.3	18.2	-45.1	175	60.5
11	30.9	-25	174	60.9	32.1	-26.9	179	60.2	30.8	-27.1	181	59.9	18	-45.3	111	76.2	17.9	-44.6	114	76.2	18.2	-45.1	106	76.3
12	30.9	-25	125	71.3	32.1	-26.9	119	71.5	30.8	-27.1	120	71.1	22.2	-41.1	102	76.7	22.3	-41.1	102	76.7	22.6	-39.4	103	76.8
13	32.4	-24.2	121	73.4	33.2	-25.5	125	73.1	32.2	-25.9	119	74.3	22.2	-6.1	139	77.4	22.3	-6.3	140	77.5	22.6	-6.2	138	77.2
14	38.9	8.8	229	79.2	39.3	9.7	247	78.9	39.3	8.8	248	78.8	29.9	-0.4	220	78	30	-4.9	230	78.1	29.9	1.2	212	77.8
15	48.7	24	487	79.7	49.2	14.5	564	79.3	48.5	14.8	559	79.3	55.2	-0.4	220	79.3	55.4	-4.9	230	78.9	55.2	1.2	212	79.7
16	61	-56.8	937	79.7	63.7	-61.6	842	79.3	64.8	-61.3	837	79.3	65.7	-13.6	423	79.3	66	-10.2	407	78.9	65.6	-20	435	79.7
17	66.1	-74.1	1034	79.7	65.2	-74	943	79.3	66.6	-73.9	942	79.3	31.4	-62.8	714	79.3	31.2	-62.5	708	78.9	30	-62.8	706	79.7
18	22.6	-76.2	1034	79.4	17.8	-74.8	943	78.9	18.7	-74.7	942	78.8	27.4	-62.8	714	79.3	26.6	-62.5	708	78.9	27.1	-62.8	706	79.7
19	15.1	-76.2	1034	74.9	15.3	-74.8	943	73.2	15.2	-74.7	942	73.1	27.4	-62.8	869	75.5	26.6	-62.5	716	74.7	27.1	-62.8	872	75.4
20	14.8	-76.2	1034	70.6	14.8	-74.8	943	71.2	15	-74.7	942	70.9	27.4	-62.8	869	61	26.6	-62.5	716	62.1	27.1	-62.8	872	60.8
21	14.8	-76.2	843	70.6	14.8	-74.8	789	71.2	15	-74.7	730	70.9	29.2	-50.1	869	66.9	28.3	-50.6	716	66.7	29.1	-49.9	872	66.7
22	14.8	-74.5	718	70.6	14.8	-71.1	789	71.2	15	-71.2	730	70.9	58.2	-50.1	869	66.9	62.2	-50.6	716	66.7	57.7	-49.9	872	66.7
23	14.8	-60.5	873	70.6	14.8	-60.2	852	71.2	15	-60.6	872	70.9	58.2	-73.9	1049	66.9	62.2	-73.7	1028	66.7	57.7	-74	1056	66.7
24	15.5	-74.9	873	70.6	19.5	-75.1	852	70.8	19.3	-74.8	872	70	76.7	-80.7	1049	66.9	76.1	-80.6	1028	66.7	76.2	-80.5	1056	66.7
25	36.4	-77.1	1182	70.5	35.3	-77.2	1294	70.8	36.4	-77	1274	70	32.7	-81.3	1049	61.4	32.3	-81.4	1028	62.1	32.8	-81.2	1056	60.8
26	30.1	-77.1	1271	68.2	28.5	-77.2	1294	69.9	30.1	-77	1274	69.5	32.7	-81.3	1049	51.7	32.3	-81.4	1028	57	32.8	-81.2	1056	59.3
27	30.1	-80.2	1271	65.4	28.5	-80	1294	64.3	30.1	-80.2	1274	65.3	32.7	-81.3	1049	51.7	32.3	-81.4	1028	57	32.8	-81.2	1056	59.3
28	30.1	-82.3	1271	64.9	28.5	-82.7	1294	64.3	30.1	-82.7	1274	64.1	32.7	-81.3	730	50.1	32.3	-81.4	959	50.1	32.8	-81.2	930	49.8
29	30.1	-83.4	1271	64.9	28.5	-83.3	1294	64.3	30.1	-83	1274	64.1	32.7	-81.3	591	50.1	32.3	-81.4	591	50.1	32.8	-81.2	590	49.8
30	30.1	-86.3	1271	57.1	28.5	-86.2	1294	57.4	30.1	-86.2	1274	54.8	32.7	-83.6	591	50.1	32.3	-83.8	591	50.1	32.8	-83.9	590	49.8
31	49.9	-86.5	982	54.1	43.5	-86.5	962	57.4	50.8	-86.5	969	54.8	42.4	-83.6	591	50.1	41.9	-83.8	591	50.1	41.2	-83.9	590	49.8
32	50.4	-86.5	982	51.9	52.1	-86.5	962	47	50.8	-86.5	969	49.2	42.4	-83.6	344	-4.4	41.9	-83.8	415	-5.7	41.2	-83.9	366	-3.4
33	27.5	-86.5	982	51.9	26.6	-86.5	962	46.8	27.7	-86.5	969	48.7	23.8	-83.6	182	-4.4	23.5	-83.8	185	-5.7	24	-83.9	181	-3.4
34	27.5	-86.7	692	0.7	26.6	-86.5	556	1.8	27.7	-86.5	560	0.5	23.8	-83.6	168	11.8	23.5	-83.8	178	18.5	24	-83.9	180	19.3
35	24	-87.4	294	11.8	22.9	-87.4	272	15.8	24.1	-87.3	270	12.3	23.8	-83.6	203	15.6	23.5	-83.8	259	27.4	24	-83.9	251	24.4
36	24	-87.4	207	11.8	22.9	-87.4	200	15.8	24.1	-87.3	200	12.3	23.8	-84.3	203	15.6	23.5	-84.2	259	27.4	24	-84.3	251	24.4
37	13.6	-87.4	178	44.1	14	-87.4	173	42.8	13.5	-87.3	173	44.3	9.8	-84.3	308	52.1	9.9	-84.2	305	57.7	9.8	-84.3	309	57.9
38	13.6	-87.4	218	44.1	14	-87.4	214	42.8	13.5	-87.3	222	44.3	9.8	-84.3	308	52.1	9.9	-84.2	335	57.7	9.8	-84.3	351	57.9
39	5.6	-87.4	303	57.5	5.8	-87.4	373	57.4	5.8	-87.3	373	57.4	9.8	-84.4	308	52.1	9.9	-84.2	335	57.7	9.8	-84.4	351	57.9
40	5.1	-87.4	409	64.2	5.2	-87.4	405	57.4	5.2	-87.3	404	62.7	9.8	-84.4	308	52.1	9.9	-84.2	335	57.7	9.8	-84.4	351	57.9
41	5.1	-87.4	461	76	5.2	-87.4	435	75.7	5.2	-87.3	455	75.5	9.8	-84.4	308	52.1	9.9	-84.2	335	57.7	9.8	-84.4	351	57.9
42	5.1	-87.4	475	76	5.2	-87.4	459	75.7	5.2	-87.3	472	75.5	9.8	-84.4	308	52.1	9.9	-84.2	335	58.6	9.8	-84.4	351	58.3
43	5.1	-87	564	76	5.2	-86.9	561	75.7	5.2	-86.9	552	75.5	9.8	-86.4	308	52.1	9.9	-86.4	492	58.6	9.8	-86.4	485	58.3
44	5.1	-87.7	564	76	5.2	-87.7	561	75.7	5.2	-87.7	552	75.5	9.8	-87.6	308	52.1	9.9	-87.6	492	58.6	9.8	-87.5	485	58.3
45	5.1	-88.4	564	76	5.2	-88.4	561	75.7	5.2	-88.4	552	75.5	10.8	-88.2	279	52.1	10.6	-88.2	492	58.6	10.9	-88.2	485	58.3
46	5.1	-88.4	564	76	5.2	-88.4	561	75.7	5.2	-88.4	552	75.5	10.8	-88.2	279	43.9	10.6	-88.2	492	58.6	10.9	-88.2	485	58.3
47	5.1	-88.4	564	76	5.2	-88.4	561	75.7	5.2	-88.4	552	75.5	10.8	-88.2	279	43.9	10.6	-88.2	492	58.6	10.9	-88.2	485	58.3
48	5.1	-88.4	564	76	6.3	-88.4	561	75.7	6.3	-88.4	552	75.5	10.8	-88.2	279	43.9	10.6	-88.2	492	58.6	10.9	-88.2	485	58.3
49	8.9	-88.4	564	76	8.9	-88.4	561	75.7	8.7	-88.4	552	75.5	13.1	-88.2	279	43.9	12.7	-88.2	492	58.6	13.1	-88.2	485	58.3
50	4.9	-88.4	564	73.8	4.9	-88.4	561	71.4	4.9	-88.4	552	72.1	4.8	-88.2	279	43.9	4.8	-88.2	492	58.6	4.8	-88.2	485	58.3

APPENDIX-B
GENERATOR DATA

Table B-1: Generator Dynamic Data

	Unit-MVA	Td0' (s)	Td0" (s)	Tq0' (s)	Tq0" (s)	H (kW-s/kVA)	Xd	Xq	Xd'	Xq'	Xd"	Xl	S1.0	S1.2
							(pu on Machine Rating)							
THERMAL UNITS														
Soldiers Pond High Inertia Synchronous Condenser	+300/-165	11	0.08	-	0.29	7.84	1.24	0.85	0.27	-	0.165	0.09	0.04	0.14
Stephenville GasTurbine #1/2	63.5	11	0.05	1.0	0.060	2.06	2.1446	1.9551	0.1706	1.2	0.1584	0.1407	0.117	0.306
Holyrood Unit #1/2	194.4	3.845	0.035	1.0	0.060	1.182	2.1142	2.045	0.2859	0.4787	0.1923	0.1607	0.1335	0.638
Holyrood Unit #3	177.2	6.8	0.06	1.0	0.060	1.29	2.15	1.94	0.26	0.55	0.22	0.1152	0.078	0.254
Hardwoods Gas Turbine #1/2	63.5	10.2	0.04	1.0	0.060	2.06	1.82	1.67	0.14	0.121	0.102	0.091	0.1581	0.3348
NLP Greenhill Gas Turbine	31.1	7.3	0.038	1.0	0.060	1.093	1.72	1.62	0.174	0.3475	0.139	0.11	0.285	0.7
CBP&P Primary Refiner 1P/3P/4P/5P/6P	10.2	1.001	0.05	1.0	0.050	1.256	1.46	1.4	0.3	0.36	0.2	0.07	0.1	0.5
CBP&P SecondaryRefiner 1S/2S/3S/4S/5S/6S	10.2	1.001	0.05	1.0	0.050	1.433	1.18	1.13	0.27	0.29	0.17	0.06	0.1	0.5
CBP&P Rejects Refiner R5/R6/R7	10.19	1.001	0.05	1.0	0.050	1.433	1.18	1.13	0.27	0.29	0.17	0.06	0.1	0.5
CBP&P Steam Unit-G2	21.8	5.246	0.033	0.2	0.314	1.1	2.4	2.17	0.26	2.17	0.188	0.119	0.135	0.584
Corner Brook Frequency Converter-60Hz	25	6	0.048	-	0.060	2.48	1.27	0.73	0.301	-	0.19	0.11	0.111	0.2862
Corner Brook Frequency Converter-50Hz	25	12.45	0.06	-	0.060	2.48	1.6	0.81	0.327	-	0.19	0.1045	0.1994	0.5814
Happy Valley GT- SynchronousCondenser Operation	26.57	10.7	0.05	3.2	0.050	1.7377	1.93	1.77	0.213	0.305	0.158	0.122	0.1843	0.6471

	Unit-MVA	Td0' (s)	Td0" (s)	Tq0" (s)	H W-s/kV	Xd	Xq	Xd'	Xd"	Xl	S1.0	S1.2
						(pu on Machine Rating)						
HYDRO UNITS												
Churchill Falls Unit A1/3/5/7/9	500	9.23	0.07	0.107	3.881	0.98	0.65	0.29	0.22	0.14	0.191	0.464
Churchill Falls Unit A2/4/6/8/10/11	500	8.0	0.071	0.25	3.807	1.00	0.62	0.28	0.22	0.14	0.191	0.464
Muskrat Falls G1/4	228.9	7.41	0.07	0.07	4.1	1.027	0.559	0.34	0.254	0.15	0.086	0.293
Bay D'Espoir Unit #1	85	6.24	0.065	0.08	5.24	1.3396	0.7497	0.3001	0.1802	0.132	0.1702	0.5621
Bay D'Espoir Unit #2	85	6.24	0.065	0.08	4.868	1.3396	0.7497	0.3001	0.1802	0.132	0.1233	0.5158
Bay D'Espoir Unit #3-6	85	6.24	0.065	0.08	5.24	1.3396	0.7497	0.3001	0.1802	0.132	0.1339	0.5504
Bay D'Espoir Unit #7	172	7.2	0.07	0.08	3.883	0.945	0.357	0.229	0.142	0.12	0.1364	0.4151
Cat Arm Unit #1/2	75.5	7.3	0.083	0.06	4.02	0.912	0.4427	0.254	0.181	0.1708	0.122	0.391
Granite Canal	45	5.8	0.042	0.042	4.0	0.711	0.48	0.35	0.23	0.1569	0.1651	0.577
Hinds Lake	83	8.24	0.035	0.17	6.6	1.2871	0.75	0.225	0.196	0.1287	0.1012	0.3529
Upper Salmon	88.4	4.345	0.04	0.06	3.5	0.86	0.594	0.3	0.215	0.12	0.084	0.3889
Paradise River	8.9	0.65	0.05	0.06	3.5	1.30	0.84	0.36	0.275	0.1	0.1189	0.3788
Deer Lake PowerCompany 60 HzUnits G1-G7	13.3	5.0	0.05	0.06	4.32	1.32	0.83	0.35	0.27745	0.2	0.11	0.48
NLP Rattling Brook Hydro Plant	15	5.0	0.05	0.06	2.5	0.9	0.54	0.23	0.16	0.100	0.11	0.48
NLP Sandy BrookHydro Plant	7	5.0	0.05	0.06	3.0	1.07	0.643	0.314	0.28	0.100	0.11	0.48
Abitibi-Consolidated - GrandFalls G4	27.5	7.37	0.035	0.035	2.96	1.545	0.7451	0.359	0.25	0.1753	0.1905	0.4741
Abitibi-Consolidated - GrandFalls G5-8	5	5.0	0.05	0.05	5.5	1.243	0.932	0.435	0.3108	0.124	0.1	0.25
ACI-CHI Star Lake Hydro Plant	20.44	3.79	0.05	0.05	6.25	1.212	1.04	0.329	0.264	0.1	0.1356	0.525
NLP Rose BlancheBrook HydroPlant	7.63	3.5	0.035	0.04	3.28	1.26	0.76	0.332	0.199	0.1	0.0545	0.2121
Deer Lake Power50 Hz G8-9	24	5.0	0.05	0.06	2.917	1.25	0.83	0.35	0.2	0.11	0.11	0.48
Deer Lake Power50 Hz Watson's Brook Unit#1/2	5.1	5.0	0.05	0.06	6.792	1.28	0.83	0.23	0.1499	0.2	0.11	0.48
Abitibi-Consolidated - BeetonUnit G9	33.3	3.8	0.032	0.032	1.827	0.98	0.56	0.41	0.29	0.28	0.2	0.75
Abitibi-Consolidated - Bishop's Falls Plant typical data	20	5.0	0.05	0.06	2.0	1.5	1.2	0.4	0.2	0.12	0.03	0.25
Rattle Brook- G1 Algonquin Power	4.02	3.14	0.039	0.062	1.052	1.399	0.775	0.306	0.186	0.107	0.156	0.276
Montagnais HQ Equivalent	30,000	-	-	-	3.6	-	-	0.22	-	-	-	-
Nova Scotia Equivalent	2,000	-	-	-	3.6	-	-	0.2	-	-	-	-

SNC·LAVALIN

nalcor energy

Lower Churchill Project

LOAD FLOW AND SHORT CIRCUIT STUDIES

SLI Document No.: 505573-480A-47ER-0003-02

Nalcor Reference No. ILK-SN-CD-8000-EL-SY-0001-01-B3

Date: 05-Apr-2012

Prepared by: for *Mohamed El Chehaly*

Verified by: *Peter Anderson*

Approved by: *Satish Sud*

REGISTERED PROFESSIONAL ENGINEER
PEG Newfoundland and Labrador
SATISH SUD
SIGNATURE
5-APR-2012
DATE
NEWFOUNDLAND & LABRADOR

Revision					Remarks
N°	By	Verif.	Appr.	Date	
02	MEC	PA	SS	05-Apr-2012	Re-Issued for Use
01	MEC	PA	SS	6-Mar-2012	Re-Issued for Use
00	MEC	PA	SS	1-Nov-2011	Issued for Use

TABLE OF CONTENTS

Page No.

List of Figures

List of Tables

Appendices

NLH Index of Substation Names

Location	ID	Location	ID
Barachoix	BCX	Holyrood	HRD
Bay d'Espoir	BDE	Howley	HLY
Bay L'Argent	BLA	Indian River	IRV
Bear Cove	BCV	Jackson's Arm	JAM
Berry Hill	BHL	Linton Lake	LLK
Bottom Brook	BBK	Long Harbour	LHR
Bottom Waters	BWT	Main Brook	MBK
Buchans	BUC	Massey Drive	MDR
Cat Arm	CAT	Monkstown	MKS
Churchill Falls	CFA	Muskrat Falls	MFA
Come-by-Chance	CBC	Oxen Pond	OPD
Coney Arm	CAM	Paradise River	PRV
Conne River	CRV	Parson's Pond	PPD
Corner Brook Freq. Conv.	CBF	Peter's Barren	PBN
Cow Head	CHD	Plum Point	PPT
Daniels Harbour	DHR	Rattle Brook	RBK
Deer Lake	DLK	Rocky Harbour	RHR
Doyles	DLS	Roddicton Woodchip	RWC
Duck Pond	DPD	Sally's Cove	SCV
English Harbour West	EHW	Soldiers Pond	SPD
Farewell Head	FHD	South Brook	SOK
Glenburnie	GLB	Springdale	SPL
Glenwood	GWD	St.Anthony Airport	STA
Grand Bay	GBY	St.Anthony Diesel Plant	SDP
Grandy Brook	GBK	Star Lake	SLK
Grand Falls Freq. Conv.	GFC	Stephenville	SVL
Granite Canal	GCL	Stony Brook	STB
Hampden	HDN	Sunnyside	SSD
Happy Valley	HVY	Upper Salmon	USL
Hardwoods	HWD	Western Avalon	WAV
Hawkes Bay	HBY	Wiltondale	WDL
Hinds Lake	HLK		

1 INTRODUCTION

This Report presents the results of the load flow studies carried out to examine the steady-state performance of the Newfoundland and Labrador (NLH) power system with the HVdc interconnections between Muskrat Falls and Soldiers Pond and between Bottom Brook and the Nova Scotia (NS) power system. The present Design Basis considers, for the Muskrat Falls-Soldiers Pond link (the “Island” link), a dc voltage level of ±350 kV and a nominal bipole rating of 900 MW and, for the Bottom Brook-Nova Scotia link (the “Maritime” link), a dc voltage level of ±200 kV and a nominal bipole rating of 500 MW. This is interpreted to mean that these rated power levels and rated voltages apply at the rectifier ends (Muskrat Falls and Bottom Brook).

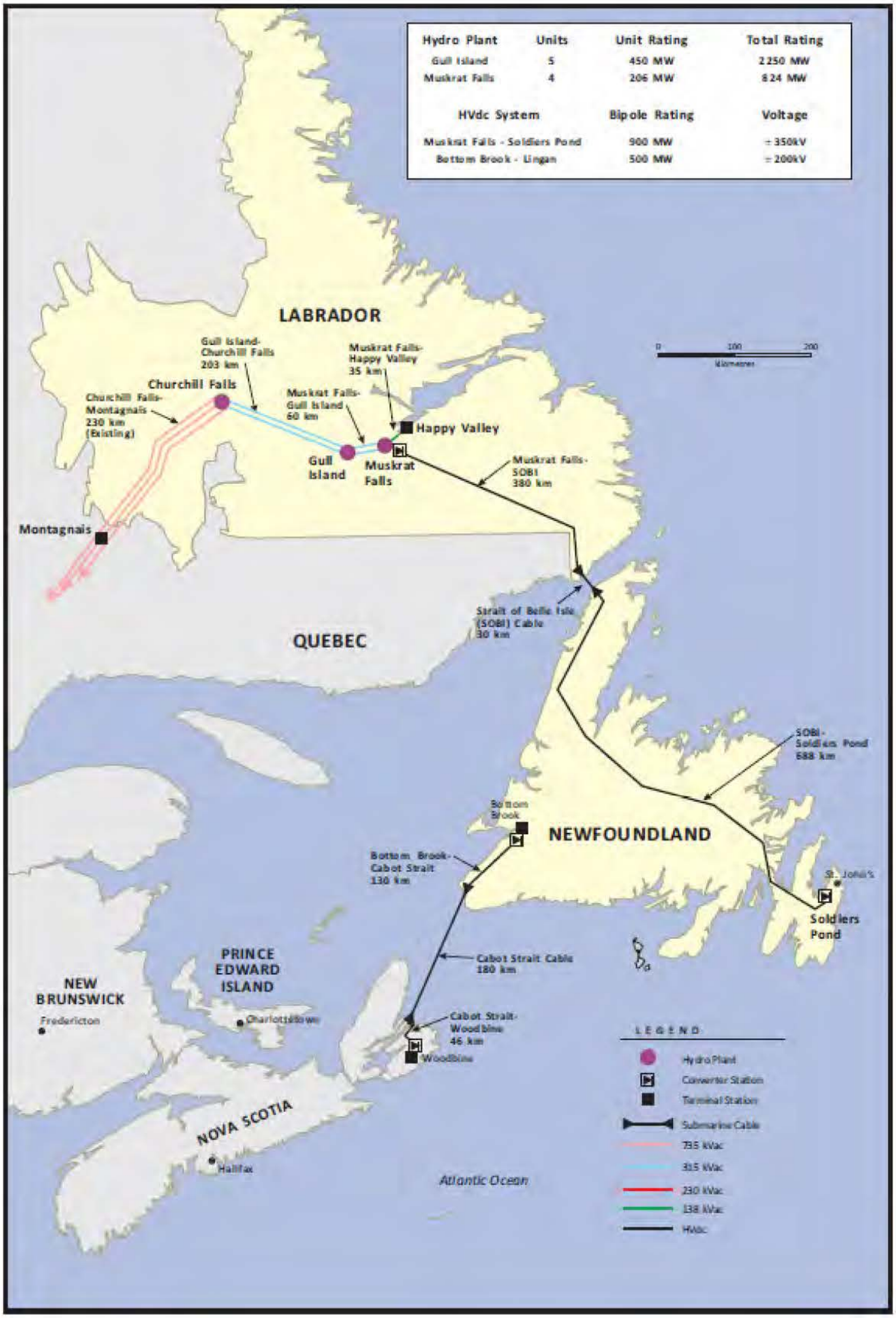
In addition to the nominal ratings above, the Design Basis calls for a 10-minute overload capability of 200% and a continuous overload capability of 150%, both in mono-polar mode on the Island link. This is to enable the island system to ride through a permanent pole outage on the Island link without having to shed load. It may be necessary, after such a permanent pole outage, to reduce the export to Nova Scotia on the Maritime link. The Island link will be essentially unidirectional from Labrador to Newfoundland, although there will be nothing in the design of the link to prevent operation in the reverse direction. The Maritime link is required to have a 500 MW continuous capability in bipolar mode in both directions.

Figure 1-1 provides an overview of the areas considered in these studies. The connection to the Trans-Energie 735 kV system in Quebec was represented by a simple equivalent at the Montagnais substation. The Emera system in Nova Scotia was represented by a simple equivalent at the inverter station of the Maritime link. The ac system between Churchill Falls and Muskrat Falls and the on-island ac system (see Figure 1-2) were modelled in detail.

Starting from the base case scenarios provided by Nalcor, the present load flow studies are designed to:

- quantify the operating modes that will be possible, both in normal and outage conditions
- define the overload requirements for the Island link,
- define the limits on the export levels on the Maritime link,
- determine the reactive compensation requirements in the Island system under a variety of operating modes,
- determine the maximum and minimum short circuit levels (fault levels) that will occur at the converter station ac busses at Muskrat Falls, Soldiers Pond and Bottom Brook,
- identify any system conditions that will result in overloads or under-voltages, requiring mitigating measures on the ac systems in Labrador and on the Island.

Figure 1-1: Project Area Map



SNC·LAVALIN	LOAD FLOW AND SHORT-CIRCUIT STUDIES	Revision		
	Nalcor Doc. No. ILK-SN-CD-8000-EL-SY-0001-01	B3	Date	Page
	SLI Doc. No. 505573-480A-47ER-0003	02	05-Apr-2012	4

Figure 1-2: Provincial Transmission Grid

2 STUDY BASIS

NALCOR provided nineteen base case scenarios for examination. These scenarios are presented in Table 2-1.

Load flow studies were carried out for each scenario, considering normal system conditions (all equipment in service) and outage conditions. In addition to pole outages on the two dc links, the automatic sequential contingency feature of PSS®E was used to examine all single contingency outages on the ac systems.

The Nalcor base case study files modelled the dc converters as generators with positive and negative real power outputs for the inverter and rectifier respectively. These models also provided reactive power control to maintain the ac bus voltage at a pre-set level. This type of model is representative of a voltage source converter (VSC), which has a controllable reactive capability. In order to make the modelling more generic and include the behaviour of a current source converter (more commonly referred to as a line commutated converter or LCC), the dc links were explicitly modelled in PSS®E as dc lines with LCC converters. Shunt capacitor banks were connected at each ac terminal bus to represent the harmonic filters that would be required with LCC converters.

Four basic generation dispatch levels were considered for these studies:

- Economic dispatch – hydro generation set to its most efficient level to optimize the hydro usage,
- Maximum Dispatch – all available generation set to its maximum output,
- Minimum Dispatch 1 – dispatch matched to light load conditions.
- Minimum Dispatch 2 – dispatch matched to extreme light load conditions.

These four dispatch levels are shown on a plant basis in Table 2-2.

The existing thermal units at Holyrood (2x194 MVA+1x177 MVA) will be converted to operate as synchronous condensers by the year 2017.

Although the transmission, subtransmission and distribution systems were modeled, only the 230 kV equipment were monitored. Any overloading on the 138 kV and the 69 kV systems are considered as local issues and therefore these are not included in the scope of work of this study.

The load flow analysis will be performed under two possible situations, that is:

Normal operating conditions (N-0): the transmission system is entirely available (no equipment has been forced out of service).

Contingency operating conditions (N-1): one component of the transmission system (line or transformer) is out of service. Only outages of equipment at the bulk transmission levels will be considered.

For each of these two operating conditions, the following criteria are applied to the analyses.

- The acceptable voltage range for operating the system under normal and contingency conditions are as follows:

Condition	Acceptable Voltage Range
Normal Conditions (N-0)	95% - 105%
Contingency Conditions (N-1)	90% - 110%

- The thermal loading of a transmission line or transformer should not exceed 100% of the following:

  - Rate A – Summer season (30 degrees C ambient) – light load and extreme light load
  - Rate B – Spring/Fall season (15 degrees C ambient) – intermediate load
  - Rate C – Winter season (0 degrees C ambient) – peak load

Table 2-1: Base Case Scenarios

No.	NLH System Load	NS Export Bottom Brook	Island Import Muskrat Falls/Soldiers Pond	Island Generation	Comments
BC-1	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 3-units @ Muskrat Falls
BC-2	Peak-2017(1552MW)	239MW	900/814MW	Maximum	Winter Peak 3-units @ Muskrat Falls
BC-3	Peak-2017(1552MW)	158MW	798/730MW	Maximum	Winter Peak
BC-4	Peak-2041(1900MW)	0MW	900/814MW	Maximum	Winter Peak
BC-5	Intermediate-2017(1100MW)	158MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-6	Intermediate-2017(1100MW)	158MW	276/268	Maximum	Spring/Fall day
BC-7	Intermediate-2017 (1100MW)	500MW	900/814MW	Economic Dispatch	Spring/Fall day
BC-8	Light (700MW)	158MW	420/400MW	Minimum	Summer day
BC-9	Light (700MW)	158MW	81/80MW	Economic Dispatch	Summer day
BC-10	Light (700MW)	500MW	900/814MW	Economic Dispatch	Summer day
BC-11	Extreme Light (420MW)	0MW	81/80MW	Economic Dispatch	Summer night
BC-12	Extreme Light (420MW)	320MW	81/80MW	Economic Dispatch	Summer night
BC-13	Extreme Light (420MW)	320MW	457/435MW	Minimum	Summer night
BC-14	Peak-2017 (1552MW)	-260MW	286/260MW-Monopole	Maximum	Winter Peak
BC-15	Intermediate-2017(1100MW)	158MW	378/333MW-Monopole	Economic Dispatch	Spring/Fall day
BC-16	Light (700MW)	500MW	638/518MW-Monopole	Minimum	Summer day
BC-17	Extreme Light (420MW)	0MW	215/200MW-Monopole	Minimum	Summer night
BC-18	Peak-2017 (1552MW)	158MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls
BC-19	Intermediate-2017(1100MW)	500MW	900/814MW	Economic Dispatch	Winter Peak 4-units @ Muskrat Falls

Table 2-2: Generation Dispatch Levels

Station	Installed Capacity(MW)	Maximum Dispatch	Economic Dispatch	Minimum Dispatch	Extreme Minimum
Thermal Plants					
Holyrood 1	175	-	-	-	-
Holyrood 2	175	SC	SC	SC	SC
Holyrood 3	160	SC	SC	SC	SC
Hardwoods 1-2	100	SC	SC	SC	SC
Stephenville	50	-	-	-	-
Sub-total Thermal	660	-	-	-	-
Hydro Plants					
Labrador					
Churchill Falls	5428	4229	4219	2963	2959
CF Net Delivery to Muskrat Falls	-	282	298	76	-26
Muskrat Falls[1]	824	618	602	824	476
Sub-total Labrador		900	900	900	450
Newfoundland					
Bay d'Espoir 1-6[2]	450	450	420	263	66
Bay d'Espoir 7	154	154	145	-	135
Cat Arm 1-2	130	130	100	36	36
Upper Salmon	84	84	78	70	-
Hinds Lake	75	75	70	-	-
Granite Canal	40	40	32	27	27
Paradise River	8	8	8	7	-
Sub-total Newfoundland		941	853	403	264
NUGS					
CBP&P		18	18	18	18
Exploits		76	76	76	76
ACI-CHI Star Lake		17.4	17.4	17.4	17.4
Algonquin Power		3.6	3.6	3.6	3.6
Sub-total NUGS		115	115	115	115
Total Generation		1956	1868	1418	829

Export to Nova Scotia		239	158	500	320
NLH Load		1552	1552	700	420
Total Load		1791	1710	1200	740

Notes:

[1]-Output of Muskrat Falls adjusted for different export levels to the Island

[2]-Bay d'Espoir #2-6 used as swing bus (exact output determined from load flow)

3 RESULTS OF THE STUDIES

Line overloads found under normal conditions and contingencies can be eliminated using the following alternatives:

- Running available combustion turbines (CTs) continuously,
- Starting the CTs following an outage which can take several minutes,
- Increasing the thermal rating of the overloaded circuits,
- Adding new circuits close to the overloaded ones,
- Adjusting the import/export levels on the HVdc interconnections,
- Re-dispatching of the generation on the Island,
- Re-locating the Bottom Brook converter station to Bay d'Espoir.

Following the Client's recommendation, the import from Labrador and the export to Nova Scotia has been adjusted to eliminate all overloads. The Client shall decide which of the mentioned alternatives will be employed to operate under the capability of the 230 kV equipment.

3.1 BASE CASE SCENARIOS: BC-1, BC-2

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-1	1552	158	900/814	Economic	Winter Peak-2017 3-units @ Muskrat Falls
BC-2	1552	239	900/814	Maximum	Winter Peak-2017 3-units @ Muskrat Falls

These scenarios consider the peak system load in the year 2017 (1,552 MW), with the maximum import on the Island link (900 MW at Muskrat Falls) and an export on the Maritime link of 158 MW at the economic on-Island dispatch level of 853 MW and an export of 239 MW at the maximum on-Island dispatch level of 941 MW. Neither of these dispatches included the gas turbines at Hardwoods (2x50 MW) and Stephenville (1x50 MW). These units are normally operated as synchronous condensers for voltage support, but can be brought into service as generators within 10 minutes. In addition two of the three units at Holyrood were operated as synchronous condensers.

The system performance for both cases is shown in Appendix A.

The overall comments on both cases are summarized below:

BC-1

Low voltage at Soldiers Pond 230 kV (< 95%) was corrected by adding a reactive power source (shunt capacitor bank) at Soldiers Pond since the two synchronous condensers at Holyrood were already operating at close to maximum output. A reactive power source output of 240 MVAr achieves a bus voltage close to 100%.

Low voltage at Bottom Brook 230 kV was corrected by adding a reactive power source (shunt capacitor bank) at Bottom Brook 230 kV. An output of 75 MVAr achieves a bus voltage close to 100%. This will be an addition to the 25 MVAr representing the filters of the HVdc.

Low voltage at Wabush 230 kV was not considered further in any of these studies as reinforcement to this area is presently under review.

No overloads were observed in the base case.

Line outages:

Removing the 230 kV circuit, TL242E, between Soldiers Pond and Hardwoods results in a 7% overload on the remaining circuit, TL201E. No mitigating measures were considered for this small overload, but it will increase in subsequent years and will need to be addressed in the future system planning.

Generator Outage:

Largest unit at Bay d'Espoir (Bay d'Espoir #7-154 MW)-The remaining generation was re-dispatched to maximum levels and the export to NS was reduced to 96 MW.

<u>BC-2</u>

With the reactive power source at Soldiers Pond 230 kV the voltage was satisfactory with an output of 240 MVAr as in BC-1.

The output of the reactive power source at Bottom Brook 230 kV increased to 130 MVAr.

No overloads were observed in the base case.

<u>Line outages:</u>

Same as in BC-1 plus the outage of the 230 kV line between Granite Canal and Bottom Brook (future line, not yet designated) required additional reactive support at Bottom Brook to prevent under-voltages at nearby buses, the reactive production increasing from 130 MVAr in the base case to 150 MVAr. This problem could also be solved by reducing the export to NS from 239 MW to 229 MW.

<u>Generator Outage:</u>

Largest unit at Bay d'Espoir (Bay d'Espoir #7-154 MW)-No generation re-dispatch is available as the units are already at maximum output. The export to NS was reduced from 239 MW to 96 MW as in BC-1 and the reactive support at Bottom Brook was disconnected to avoid over-voltages in that area.

3.2 BASE CASE SCENARIO: BC-3

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-3	1552	158	798/730	Maximum	Winter Peak-2017

In this case, a reduced power export of 798 MW from Labrador over the Island link was considered, the island generation was dispatched to its maximum and the export to NS over the Maritime link was set at 158 MW. The system performance is shown in Appendix A. The same general observations and comments apply to this case as described for BC-1 and BC-2, however for the loss of the largest unit at Bay d'Espoir, a limited number of options are available as the island generation is already at its maximum:

- Increase the export from Labrador on the Island link from 798 MW to 900 MW. If this power increase cannot be supplied by Muskrat Falls, it will have to come from Churchill Falls,

- Reduce the export to NS to 10 MW,

- A combination of the above; for example, increasing the export over the Island link by 75 MW and reducing the export to NS by 75 MW.

3.3 POLE OUTAGES

Following on from the base cases presented above, the effect of a permanent pole outage on the Island link was examined. It was assumed that following a pole outage, the island generation would automatically be re-dispatched up to its maximum under AGC and operator control. Thus, in terms of the island generation dispatch, scenarios BC-1, BC-2 and BC-3 become identical. The following table shows the required capacity on the remaining, healthy pole of the Island link, considering different courses of action with respect to the Maritime link. The percentage loadings for the Island link are based on a nominal capacity of 450 MW per pole. The export on the Maritime link of 158 MW corresponds to the economic dispatch of the island generation. The export level of 239 MW corresponds to maximum island dispatch.

Monopole operation of the Island link is simulated by taking into consideration the electrode lines. The resistance of these lines is added to the resistance of the healthy pole which includes the overhead line resistance and the resistance of the submarine cable.

Table 3-1: Healthy Pole Loading Levels following a Pole Outage

Maritime Link(MW)		Island Link(MW)		
Pre-fault	Post-fault	Pre-fault	Post-fault	
158	158	900	1010	224%
158	100	900	900	200%
158	0	900	730	162%
239	239	900	1200	267%
239	100	900	900	200%
239	0	900	730	162%

The maximum loading (200%) is reached with an export to Nova Scotia reduced to 100 MW. The loadings shown above would apply for a 10-minute period, during which time the 3x50 MW gas turbines at Hardwoods and Stephenville could be brought into service. Following this action, the loadings above on the Island link could be reduced by approximately 150 MW. The maximum loading of 900 MW/200 % would then be reduced to 650 MW/145%. These results confirm the Design Basis requirement for a 10-minute overload rating of 200% of nominal rating and a continuous overload rating of 150% of nominal rating, provided that in the event of a pole outage the export on the Maritime link must be reduced to no more than 100 MW and the Island generation must be run up to its maximum. If the Island generation cannot be taken to its maximum, then the export on the Maritime link would need to be reduced to zero.

3.4 BASE CASE SCENARIO BC-4

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-4	1900	0	900/814	Maximum	Winter Peak-2041

This scenario considers a long-term future year (2041) in which the Island link is operating at 900 MW, the island generation is at its maximum level and the export to NS over the Maritime link is set at 0 MW. In this condition, the system is operating with no reserve and any generator outage or pole outage on the Island link will result in load shedding. No further studies have been carried out on this scenario at this time. The system performance is shown in Appendix A.

3.5 BASE CASE SCENARIO BC-5

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-5	1100	158	900/814	Economic	Spring/Fall day-2017

This scenario considers the full export from Labrador and the nominal export to Nova Scotia during the Spring/Fall seasons. In this scenario, lower ratings apply to the transmission lines due to the higher ambient temperature.

The system performance is shown in Appendix A.

Because of the reduced load levels, the reactive compensation required at Soldiers Pond reduced from 240 MVAr to 140 MVAr and the reactive support at Bottom Brook reduced from 75 MVAr to 45 MVAr.

Line Outages:

The outage of the Western Avalon-Soldiers Pond 230 kV line TL217W (load flow circuit #1) results in a 16% overload on 230 kV line TL201W (load flow circuit #2) because of the reduced line rating in the Spring/Fall seasons.

Generator Outage:

The outage of the largest generator (Upper Salmon-75MW) will require a reduction in the export to Nova Scotia. The spinning reserve on the system for this scenario is only 40 MW, spread over the Bay d'Espoir running units (21 MW), the unit at Granite Canal (12 MW) and the Hinds Lake (6 MW) and Paradise River (1 MW) units. Thus a reduction in the export to NS of 40 MW should be sufficient to correct this imbalance or an additional unit at Bay d'Espoir could be connected to provide sufficient spinning reserve.

3.6 BASE CASE SCENARIO BC-6

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-6	1100	158	276/268	Maximum	Spring/Fall day-2017

This scenario considers a reduced export from Labrador and the nominal export to Nova Scotia during the Spring/Fall seasons. In this scenario, as a result of the lower import from Labrador, the island generation is set to its maximum. The system performance is shown in Appendix A.

No under-voltage or overload was seen for any line outage.

Generator Outage:

The loss of the largest unit at Bay d'Espoir (Bay d'Espoir #7-154 MW) would require the reduction of the export to NS to zero since the island generation is set at maximum output. Alternatively, if the power is available, an increase in the import from Labrador would correct this imbalance or, as seen before, a combination of these two measures could be used.

3.7 BASE CASE SCENARIO BC-7

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-7	1100	500	900/814	Economic	Spring/Fall day-2017

This scenario is similar to BC-5 except that the export to Nova Scotia is increased up to 500 MW by running three additional smaller units and the large unit at Bay d'Espoir.

The system performance is shown in Appendix A.

The additional export to Nova Scotia requires a significant increase in the reactive support at Bottom Brook with 320 MVAr being required to maintain a bus voltage of 100% in the base case.

<u>Line Outages:</u>

With an outage of the 230 kV line from Granite Canal to Bottom Brook (future line, not yet designated), the reactive support required at Bottom Brook to support the export of 500 MW to NS increases from 320 MVAr to 585 MVAr and by setting the voltage at Bottom Brook to 101%. This outage would also create under-voltages at Buchans, Stony Brook and Abitibi Consolidated Grand Falls. Alternatively, a reduction in the export to NS from 500 MW to 400 MW would require 300 MVAr of reactive support (close to the base case requirement).

A significant number of line overloads were observed under the following line outage conditions:

- Outage: Bottom Brook-Massey Drive (TL211)
  - Overload: Bottom Brook-Buchans (TL233)-115%
- Outage: Bottom Brook- Buchans(TL233)
  - Overload: Bottom Brook- Massey Drive (TL211)-134%

- Overload: Massey Drive-Buchans (TL228)-146%

- Outage: Granite Canal-Bottom Brook (future line, not yet designated)
  - Overload: Bottom Brook-Massey Drive (TL211)-137%
  - Overload: Bottom Brook-Buchans (TL233)-127%
  - Overload: Massey Drive-Buchans (TL228)-151%
  - Overload: Buchans-Stony Brook (TL205)-132%
  - Overload: Stony Brook-Bay d'Espoir (TL204 and TL231)-101%
- Outage: Massey Drive- Buchans (TL228)
  - Overload: Bottom Brook-Buchans (TL233)-109%
- Outage: Buchans-Stony Brook (TL232)
  - Overload: Buchans-Stony Brook (TL205)-128%
- Outage: Bay d'Espoir-Upper Salmon (TL234)
  - Overload: Bottom Brook-Massey Drive (TL211)-102%
  - Overload: Massey Drive-Buchans (TL228)-108%
- Outage: Western Avalon-Soldiers Pond (TL217W)
  - Overload: Western Avalon-Soldiers Pond (TL201W)-115%
- Outage: Granite Canal-Upper Salmon (TL263)
  - Overload: Bottom Brook-Massey Drive (TL211)-124%
  - Overload: Bottom Brook-Buchans (TL233)-114%
  - Overload: Massey Drive-Buchans (TL228)-134%
  - Overload: Buchans-Stony Brook (TL205)-118%

A reduction in the export to NS to 350 MW with an accompanying reduction in the Island link to 750 MW would remove all of the above overloads. It should be noted that other alternatives can be employed as mentioned earlier.

Generator Outage:

Largest unit at Bay d'Espoir (Bay d'Espoir #7-135 MW)-The remaining generation was re-dispatched to maximum levels.

3.8 BASE CASE SCENARIO BC-8

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-8	700	158	420/400	Minimum	Summer day-2017

This scenario considers light load conditions corresponding to a summer day with a reduced import from Labrador and the nominal export of 158 MW to Nova Scotia. Due to the higher ambient temperature, lower ratings apply to the transmission lines. The system performance is shown in Appendix A.

No under-voltage or overload was seen for any line outage.

Generator Outage:

The loss of the largest generator (Bay d'Espoir #7-135 MW) would require either two additional units at Bay d'Espoir to be running as spinning reserve or the export to NS would have to be reduced from 158 MW to 90 MW.

3.9 BASE CASE SCENARIO BC-9

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-9	700	158	81/80	Economic	Summer day-2017

This scenario is similar to BC-8 but with a reduced import from Labrador compensated by increased generation on the Island.

The system performance is shown in Appendix A.

Line Outages:

For the outage of one 230 kV circuit between Bay d'Espoir and Sunnyside (TL202 or TL206) the loading on the remaining circuit reaches 104%. These overloads can be alleviated by increasing the import from the LIL to 100 MW.

Generator Outage:

Largest unit at Bay d'Espoir (Bay d'Espoir #7-135 MW)-The remaining generation was re-dispatched to maximum levels.

3.10 BASE CASE SCENARIO BC-10

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-10	700	500	900/814	Economic	Summer day-2017

This scenario considers the full import from Labrador and an increased export of 500 MW to Nova Scotia under light load conditions in the summer season.

The system performance is shown in Appendix A.

Again, because of the high export level to NS, reactive support of 300 MVAr was required at Bottom Brook.

Even in the base case, the following line overloads were noted:

- Massey Drive-Buchans (TL228)-122%
- Buchans-Stony Brook (TL205)-102%
- Western Avalon-Soldiers Pond (TL201W)-141%

Line Outages:

Line outages between Bottom Brook and Granite Canal (future line, not yet designated) and Granite Canal and Upper Salmon (TL263) lead to system non-convergence. To counter this problem, the export to Nova Scotia is reduced to 400 MW (the import from Labrador is reduced to 800 MW on the rectifier side).

A number of 230 kV line outages resulted in overloading of other 230 kV lines before decreasing the export to Nova Scotia (from 500 MW to 400 MW). Lines that are overloaded under N-0 are omitted from this part:

- Outage: Deer Lake-Cat Arm (TL247)
  - Overload: Bottom Brook-Buchans (TL233)-103%
  - Overload: Granite Canal-Upper Salmon (TL263)-106%
- Outage: Deer Lake-Massey Drive (TL248)
  - Overload: Bottom Brook-Buchans (TL233)-103%
  - Overload: Granite Canal-Upper Salmon (TL263)-103%
- Outage: Bottom Brook-Massey Drive (TL211)
  - Overload: Bottom Brook-Buchans (TL233)-162%
  - Overload: Granite Canal-Upper Salmon (TL263)-123%
- Outage: Bottom Brook-Buchans (TL233)
  - Overload: Bottom Brook-Massey Drive (TL211)-185%
  - Overload: Granite Canal-Upper Salmon (TL263)-131%
- Outage: Massey Drive-Buchans (TL228)
  - Overload: Bottom Brook- Buchans (TL233)-166%
  - Overload: Granite Canal-Upper Salmon (TL263)-123%
- Outage: Buchans-Stony Brook (TL205)
  - Overload: Buchans-Stony Brook (TL232)-137%
  - Overload: Granite Canal-Upper Salmon (TL263)-114%
- Outage: Buchans-Stony Brook (TL232)

- Overload: Granite Canal-Upper Salmon (TL263)-117%

- Outage: Stony Brook-Bay d'Espoir (TL204)
  - Overload: Stony Brook-Bay d'Espoir (TL231)-139%
  - Overload: Granite Canal-Upper Salmon (TL263)-120%
- Outage: Stony Brook-Bay d'Espoir (TL231)
  - Overload: Stony Brook-Bay d'Espoir (TL204)-139%
  - Overload: Granite Canal-Upper Salmon (TL263)-120%
- Outage: Stony Brook-Abitibi Consolidated Grand Falls (TL235)
  - Overload: Granite Canal-Upper Salmon (TL263)-103%
- Outage: Bay d'Espoir-Upper Salmon (TL234)
  - Overload: Bottom Brook-Massey Drive (TL211)-140%
  - Overload: Bottom Brook-Buchans (TL233)-140%
  - Overload: Buchans-Stony Brook (TL232)-110%
  - Overload: Stony Brook-Bay d'Espoir (TL204 and TL231)-111%
- Outage: Western Avalon-Come by Chance (TL237)
  - Overload: Western Avalon-Sunnyside (TL203)-120%
- Outage: Western Avalon-Soldiers Pond (TL217W)
  - Overload: Granite Canal-Upper Salmon (TL263)-101%
- Outage: Western Avalon-Soldiers Pond (TL201W)
  - Overload: Western Avalon-Soldiers Pond (TL217W)-138%
  - Overload: Granite Canal-Upper Salmon (TL263)-101%

Reducing the export to NS from 500 MW to 100 MW removed all of the above overloads including the ones found under N-0. It should be noted that other alternatives can be employed as mentioned earlier.

Generator Outage:

Largest unit at Upper Salmon (75MW) -The remaining generation was re-dispatched to maximum levels.

3.11 BASE CASE SCENARIO BC-11

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-11	420	0	81/80	Economic	Summer night-2017

This scenario considers the system under extreme light load conditions, corresponding to a summer night. With no export to Nova Scotia and an economic generation dispatch, the import from Labrador is reduced to its minimum level (<10% of the rated value). The system performance is shown in Appendix A.

No under-voltage or overload was seen for any line outage.

Generator Outage:

Outage of the largest generator (Upper Salmon-75 MW) would require either two additional units at Bay d'Espoir as spinning reserve or an increase in the Island link import from 81 MW to 108 MW.

3.12 BASE CASE SCENARIO BC-12

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-12	420	320	81/80	Economic	Summer night-2017

This scenario is similar to BC-11 but with an export to Nova Scotia of 320 MW provided by additional on-island generation.

The system performance is shown in Appendix A.

Line Outages:

The following 230 kV line outages resulted in overloading of other 230 kV lines:

- Outage: Bottom Brook-Buchans (TL233)
    - Overload: Bottom Brook-Massey Drive (TL211)-114%
- Outage: Bottom Brook-Granite Canal (future line, not yet designated)
    - Overload: Bottom Brook-Massey Drive (TL211)-104%

A reduction in the export to NS with an accompanying reduction in the import over the Island link would relieve these overloads. However, the Island link is already operating at its minimum level (< 10% rated capacity). A reduction of 50 MW in the export to NS would remove the above line overloads and either the Island link can be switched off or the on-island generation can be reduced to compensate for this. It should be noted that other alternatives can be employed as mentioned earlier.

Generator Outage:

Largest unit at Upper Salmon (75MW) -The remaining generation was re-dispatched to maximum levels.

3.13 BASE CASE SCENARIO BC-13

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-13	420	320	457/435	Minimum	Summer night-2017

This scenario is similar to BC-12 except that the export to Nova Scotia is provided by the import from Labrador rather than on-island generation.

The system performance is shown in Appendix A.

Line Outages:

The following 230 kV line outages result in overloading of other 230 kV lines:

- Outage: Bottom Brook-Buchans (TL233)
    - Overload: Bottom Brook-Massey Drive (TL211)-110%

- Overload: Massey Drive-Buchans (TL228)-124%

- Outage: Bottom Brook-Granite Canal (future line, not yet designated)
  - Overload: Massey Drive-Buchans (TL228)-106%

- Outage: Buchans-Stony Brook (TL232)
  - Overload: Buchans-Stony Brook (TL205)-106%

- Outage: Western Avalon-Soldiers Pond (TL217W)
  - Overload: Western Avalon-Soldiers Pond (TL201W)-140%

A reduction in the export to NS to 240 MW, with an accompanying reduction in the Island link to 372 MW, removes these overloads. It should be noted that other alternatives can be employed as mentioned earlier.

Generator Outage:

The outage of the largest generator (Bay d'Espoir #7-135 MW) would require the addition of two units at Bay d'Espoir as spinning reserve or a reduction in the export to NS to 240 MW.

3.14 BASE CASE SCENARIO BC-14

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-14	1552	-260	286/260Monopole	Maximum	Winter Peak-2017

This scenario considers a permanent pole outage on the Island link under peak load conditions with the remaining pole operating at 62% of rated capacity and the balance of load being supplied by an import of 260 MW from Nova Scotia.

The system performance is shown in Appendix A.

Line Outages:

Although any line or generator outage under these conditions could be considered as a double contingency, these outages were nonetheless examined. The outage of one 230 kV circuit between Bay d'Espoir and Sunnyside (TL202 or TL206), or Bay d'Espoir and Western Avalon (future line, not yet designated) or Western Avalon and

Soldiers Pond (TL217W or TL201W) required reactive support at Soldiers Pond. The maximum support level was 204 MVAr for the outage of the Bay d'Espoir-Western Avalon line (future line, not yet designated).

Generator Outage:

The outage of the largest generator (Bay d'Espoir #7-154MW) would require an increase in the import from Labrador or Nova Scotia of 135 MW.

3.15 BASE CASE SCENARIO BC-15

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-15	1100	158	378/333Monopole	Economic	Spring/Fall day-2017

This scenario considers a permanent pole outage under intermediate load conditions with the healthy pole operating at 80% of rated capacity and with Nova Scotia being supplied a nominal export of 158 MW.

The system performance is shown in Appendix A.

Although any line or generator outage under these conditions could be considered as a double contingency, these outages were nonetheless examined. No under-voltage or overload was seen for any line outage. For the outage of the largest generator (Bay d'Espoir #7-150 MW), the export to Nova Scotia would need to be reduced from 158 MW to 76 MW or the import from Labrador is increased from 378 MW to 555 MW. It should be noted that other alternatives can be employed as mentioned earlier.

3.16 BASE CASE SCENARIO BC-16

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-16	700	500	638/518Monopole	Minimum	Summer day-2017

This scenario considers a permanent pole outage under light load conditions with the healthy pole operating at 132% of rated capacity and an increased export of 500 MW to Nova Scotia, supplied from the Island link with minimum on-island generation.

The system performance is shown in Appendix A.

Because of the high export to Nova Scotia, the reactive support required at Bottom Brook is 240 MVAr. The 230 kV line between Massey Drive and Bottom Brook (TL211) is overloaded at 110% of its summer rating.

Line Outages:

The following 230 kV line outages resulted in overloads in other 230 kV lines. Lines that are overloaded under N-0 are omitted from this part:

- Outage: Deer Lake-Cat Arm (TL247)
  - Overload: Massey Drive-Buchans (TL228)-115%
- Outage: Deer Lake-Massey Drive (TL248)
  - Overload: Massey Drive-Buchans (TL228)-117%
- Outage: Bottom Brook-Massey Drive (TL211)
  - Overload: Bottom Brook-Buchans (TL233)-164%
  - Overload: Granite Canal-Upper Salmon (TL263)-113%
- Outage: Bottom Brook-Buchans (TL233)
  - Overload: Massey Drive-Buchans (TL228)-178%
  - Overload: Granite Canal-Upper Salmon (TL263)-110%
- Outage: Bottom Brook-Granite Canal (future line, not yet designated)
  - Overload: Massey Drive-Buchans (TL228)-160%
  - Overload: Buchans-Stony Brook (TL205)-146%
  - Overload: Buchans-Stony Brook (TL232)-109%
  - Overload: Stony Brook-Bay d'Espoir (TL204 and TL231)-109%
  - Overload: Bottom Brook-Buchans (TL233)-148%
- Outage: Massey Drive-Buchans (TL228)
  - Overload: Bottom Brook-Buchans (TL233)-137%
- Outage: Buchans-Stony Brook (TL205)
  - Overload: Buchans-Stony Brook (TL232)-111%

- Outage: Buchans-Stony Brook (TL232)
  - Overload: Buchans-Stony Brook (TL205)-156%

- Outage: Stony Brook-Bay d'Espoir (TL204)
  - Overload: Stony Brook-Bay d'Espoir (TL231)-110%

- Outage: Stony Brook-Bay d'Espoir (TL231)
  - Overload: Stony Brook-Bay d'Espoir (TL204)-110%

- Outage: Bay d'Espoir-Upper Salmon (TL234)
  - Overload: Bottom Brook-Buchans (TL233)-115%
  - Overload: Massey Drive-Buchans (TL228)-122%
  - Overload: Buchans-Stony Brook (TL205)-111%

- Outage: Western Avalon-Soldiers Pond (TL217W)
  - Overload: Western Avalon-Soldiers Pond (TL201W)-120%

- Outage: Granite Canal-Upper Salmon (TL263)
  - Overload: Bottom Brook-Buchans (TL233)-138%
  - Overload: Massey Drive-Buchans (TL228)-148%
  - Overload: Buchans-Stony Brook (TL205)-135%

All the above overloads could be removed by reducing the export to NS to 250 MW with an accompanying reduction in the Island link import to 344 MW. It should be noted that other alternatives can be employed as mentioned earlier.

Generator Outage:

Largest unit at Bay d'Espoir (Bay d'Espoir #7-124 MW)-The remaining generation was re-dispatched to maximum levels.

3.17 BASE CASE SCENARIO BC-17

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-17	420	0	215/200Monopole	Minimum	Summer night-2017

This scenario considers a permanent pole outage under extreme light load conditions with the healthy pole operating at 47% of rated capacity and no export to Nova Scotia and minimum on-island generation. The balance of load is supplied from the Island link.

The system performance is shown in Appendix A.

An over-voltage (> 105%) was observed at Bottom Brook with no export to Nova Scotia. This was corrected with a 100 MVAr shunt reactor.

No under-voltage or overload was seen for any line outage.

Generator Outage:

For the outage of the largest generator (Bay d'Espoir #1-61 MW), an additional unit at Bay d'Espoir would be required as spinning reserve or the import on the Island link could be increased by 20 MW, with all connected generators increasing to maximum dispatch.

3.18 BASE CASE SCENARIO BC-18

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-18	1552	158	900/814	Economic	Winter Peak-2017 4-units @ Muskrat Falls

This scenario is the same as BC-1 except that all four units at Muskrat Falls were considered to be operating.

The system performance is shown in Appendix A.

The performance of the system was identical to that seen in BC-1.

3.19 BASE CASE SCENARIO BC-19

No.	NLH System Load(MW)	NS Export BBK(MW)	Island Import MFA/SPD(MW)	Island Generation	Comments
BC-19	1100	500	900/814	Economic	Winter Peak-2017 4-units @ Muskrat Falls

This scenario is the same as BC-7 except that all four units at Muskrat Falls were considered to be operating.

The system performance is shown in Appendix A.

The performance was virtually identical to that seen in BC-7.

4 SHORT CIRCUIT LEVELS

In terms of short-circuit levels, two major considerations are of interest:

- Maximum fault levels in terms of the fault-interrupting capabilities of the existing and future switchgear,
- Minimum fault levels combined with maximum converter loadings to determine the effective short-circuit ratio (ESCR) at the converter terminals. This parameter provides a useful indication of satisfactory converter operation and the risk of commutation failures.

Maximum short-circuit levels were determined using Scenario BC-4 (winter peak-2041) since this scenario considers all available generation on the island to be connected. The fault levels obtained were also checked using Scenario BC-2 (winter peak-2017) with a maximum generation dispatch and the fourth unit at Muskrat Falls connected.

For minimum fault levels combined with maximum converter loadings, the following scenarios were considered:

<u>Muskrat Falls Converter</u>

- BC-1: 3 units at Muskrat Falls with a converter load of 900 MW,
- BC-13: 2 units at Muskrat Falls with a converter load of 457 MW

Although BC-13 actually considers three units to be operating at Muskrat Falls, this scenario was used with only two units at Muskrat Falls to examine the impact on the fault level at the Muskrat Falls converter station.

<u>Soldiers Pond Converter</u>

- BC-5: 814 MW converter load with an economic dispatch for an intermediate load level of 1100 MW,
- BC-13: 435 MW converter load with an extreme minimum load level of 400 MW.

<u>Bottom Brook Converter</u>

- BC-10: 500 MW converter load with a light load level of 700 MW,

- BC-13: 320 MW converter load with an extreme minimum load of 420 MW.

4.1 MAXIMUM FAULT LEVELS

Under maximum generation conditions, the following table shows the maximum short-circuit level at each converter bus and the highest value of fault level on the island 230 kV and 138 kV system.

Table 4-1: Maximum Fault Levels

Station	kV	Three-phase		Single-phase	
		kA	MVA	kA	MVA
Muskrat Falls	315	6.2	3,400	8.0	4,350
Soldiers Pond	230	6.1	2,425	7.5	3,000
Bottom Brook	230	3.8	1,525	3.9	1,550
Bay d'Espoir	230	9.6	3,850	11.5	4,600
Stony Brook	138	5.9	2,200	7.3	2,725

It can be seen that none of the above fault levels are excessive and are all well within typical switchgear fault-interrupting capabilities.

The following table shows the same case with all machines at Holyrood connected and with 2x150 MVA synchronous condensers at Soldiers Pond.

Table 4-2: Maximum Fault Levels with 2x 150 MVAr SC at SPD

Station	kV	Three-phase		Single-phase	
		kA	MVA	kA	MVA
Muskrat Falls	315	6.2	3,400	8.0	4,350
Soldiers Pond	230	7.4	2,960	8.8	3,510
Bottom Brook	230	3.8	1,525	3.9	1,550
Bay d'Espoir	230	9.8	3,920	11.7	4,670
Stony Brook	138	5.9	1,410	7.3	1,740

The fault level will vary depending on the number and the size of synchronous condensers at Soldiers Pond. The following table shows the fault level of different configuration of synchronous condensers at Soldiers Pond.

Table 4-3: Maximum Fault Levels with Different SCs at SPD

Station	kV	Three-phase		Single-phase	
		kA	MVA	kA	MVA
No SC	230	6.1	2,425	7.5	3,000
2x150 MVAr	230	7.4	2,960	8.8	3,510
3x150 MVAr	230	8.1	3,228	10.8	4,275
2x300 MVAr	230	8.7	3,495	11.4	4,530

4.2 MINIMUM FAULT LEVELS

The following tables show the minimum 3-phase fault level and effective short-circuit ratio (ESCR) for the specific scenarios considered under normal conditions with all equipment in service. The ESCR was calculated using a typical ratio between the shunt compensation obtained from filters and the dc power level of 25% (converter reactive requirement is typically 50% of the dc power level and the filters typically provide 50% of this reactive power requirement).

$$ESCR = \frac{MVA_{SC} - Q_F}{P_{dc}} = \frac{MVA_{SC}}{P_{dc}} - 0.25$$

Table 4-4: Muskrat Falls Converter Station

Scenario	Converter MW	Min.Fault Level MVA	ESCR
BC-1	900	3,390	3.52
BC-13	457	2,755	5.85

Table 4-5: Soldiers Pond Converter Station

Scenario	Converter MW	Min.Fault Level MVA	ESCR
BC-5/10	814	2,310	2.52
BC-13	435	2,240	4.90

Table 4-6: Bottom Brook Converter Station

Scenario	Converter MW	Min.Fault Level MVA	ESCR
BC-10	500	1,345	2.44
BC-13	320	1,250	3.66

The minimum ESCR occurs for scenario BC-1 for Muskrat Falls, scenario BC-5 and BC-10 for Soldiers Pond and scenario BC-10 for Bottom Brook. All the minimum ESCRs occur at the rated power level for each converter station.

All the ESCRs are equal to or greater than the normally recommended minimum of 2.5 except for Bottom Brook where the value is less than 2.5. These values are for normal system conditions and will be lower under line outage conditions.

The worst line outage was analyzed for each of the scenarios above that resulted in minimum values of ESCR. The results are shown below.

Table 4-7: Minimum ESCR under Line Outage Conditions

Station	Scenario	Converter MW	Disconnected Line	Min.Fault Level MVA	ESCR
Muskrat Falls	BC-1	900	CHF-MFA	2,730	2.78
Soldiers Pond	BC-5	814	SPD-WAV (TL217W)	2,190	2.38
Bottom Brook	BC-10	500	BBK-MDR (TL211)	905	1.56

While the ESCR at Muskrat Falls remained above the minimum value of 2.5, the value at Soldiers Pond was marginally below 2.5 and the value at Bottom Brook was less than 2.0.

5 CONCLUSIONS

5.1 AC SYSTEM MITIGATING MEASURES

Although reinforcements to the ac system within Newfoundland are not within the scope of this present study, it is necessary to determine the impacts of outages so that the alternative mitigating measures can be examined with respect to defining the required operating modes of the two HVdc links.

Line outage, pole outage and generator outage cases were examined for the four distinct load levels corresponding to Winter peak, Spring/Fall daytime, Summer daytime and Summer night-time. Only the 230 kV was monitored and any violations were reported. Throughout all the cases examined, in order to avoid line overloads, load shedding within Newfoundland, or excessive levels of reactive support, a common element appears to be that in the event of a line, pole or generator outage the power transfer to Nova Scotia could be reduced to ensure satisfactory system performance. Other alternatives were proposed as well to eliminate overloads such as running CTs continuously or starting them following an outage, increasing the thermal capability of the overloaded circuits, adding new circuits, re-dispatching the Island generation and re-locating the converter of the ML Link.

In a number of cases, the reduction in the export to Nova Scotia would need to be accompanied by a reduction in the power sent over the Island link. Such measures are required to relieve overloads within the Soldiers Pond-Western Avalon-Bay d'Espoir corridor. In other cases, a reduction in only the export to Nova Scotia is necessary to relieve overloads within the Bay d'Espoir-Stony Brook-Buchans-Massey Drive/Bottom Brook and Bay d'Espoir-Upper Salmon-Granite Canal-Bottom Brook corridors.

The alternative to such mitigating measures would be to reinforce each of the above corridors with an additional transmission circuit. The Granite Canal-Bottom Brook transmission line is already a reinforcement of the existing system.

It was also found necessary to provide significant levels of reactive support at both the Soldiers Pond converter station (240 MVAr) and the Bottom Brook converter station (+320/-100 MVAr).

The variations in the reactive support required at Bottom Brook, together with a need to change the ordered dc power whenever there is an outage on the ac system would suggest that the compensation should be provided in the form of a static var compensators, synchronous condensers, or the converter may be of the VSC type with an inherent reactive control capability and lower requirements in terms of short-circuit ratio. The variations in reactive support are not as frequent at Soldiers Pond as they are at Bottom Brook. The need for specialized reactive support equipment (SVC or synchronous condenser) will be determined in the stability studies of the interconnected network.

Given the above requirements for the Bottom Brook converter station, the prospect must be raised as to the suitability of Bottom Brook as a location for the converter station of the Maritime link. The short-circuit level is low (ESCR <2.5), significant levels of reactive support are required and in the event of an outage on the Island system, the export to Nova Scotia has to be reduced to avoid overloading the transmission lines in the western part of the island. This would suggest that the Bay d'Espoir generating station would prove to be a more suitable location for this converter. The short-circuit level is higher, the lines in the western part of the system do not need to carry the export power and there is a significant reactive capability at the generating station. This would reduce the number of outage situations requiring a reduction in the export to Nova Scotia. It would also avoid the need to build the transmission link between Granite Canal and Bottom Brook but would, however, require additional dc transmission from the submarine cable transition station in Newfoundland to Bay d'Espoir.

5.2 OPERATING MODES

The steady-state operating modes of both the Island link and the Maritime link were examined over the following dc power ranges:

- Island link: 900 MW to 81 MW
- Maritime link: 500 MW export to 260 MW import

Pole outage cases confirmed the Design Basis requirements for a 200% overload capability for 10 minutes and a continuous overload capability of 150% in mono-polar mode.

In addition to operation over the ranges stated above, certain operating levels, as defined in the base case scenarios, are not sustainable under certain line and/or generator outage conditions and reductions in the power transfer levels will need to be made in the event of line outages.

For the individual base case scenarios, the following adjustments to the power transfer levels were identified:

BC-1/BC-2 (Winter Peak)

For the loss of the largest generator at Bay d'Espoir:

- Reduce export on the Maritime link from 158 MW (BC-1) or 239 MW (BC-2) to 96 MW

BC-3 (Winter Peak)

For the loss of the largest generator at Bay d'Espoir:

- Reduce export on the Maritime link from 158 MW to 10 MW.

BC-5 (Spring/Fall Peak)

For the loss of circuit #1 between Soldiers Pond and Western Avalon (TL217W);

- Reduce the export on the Maritime link from 158 MW to 98 MW.
- Reduce the import from the Island link from 814 MW to 774 MW.

For the loss of the largest generator at Upper Salmon:

- Reduce export on the Maritime link from 158 MW to 124 MW.

BC-6 (Spring/Fall Peak)

For the loss of the largest generator at Bay d'Espoir:

- Reduce export on the Maritime link from 158 MW to zero.

BC-7 (Spring/Fall Peak)

For the loss of almost any 230 kV line on the Soldiers Pond-Bottom Brook corridor:

- Reduce export on the Maritime link from 500 MW to 350 MW,
- Reduce import from the Island link from 814 MW to 664 MW.

BC-8 (Summer Light)

For the loss of the largest generator at Bay d'Espoir:

- Reduce export on the Maritime link from 158 MW to 90 MW.

BC-9 (Summer Light)

No operating reductions required.

BC-10 (Summer Light)

For the loss of almost any 230 kV line on the Soldiers Pond-Bottom Brook corridor:

- Reduce export on the Maritime link from 500 MW to 100 MW,
- Reduce import from the Island link from 814 MW to 414 MW.

BC-11 (Summer Extreme Light)

For the loss of the largest generator at Upper Salmon:

- Increase import on the Island link from 81 MW to 108 MW

.**BC-12 (Summer Extreme Light)**

For the loss of the 230 kV line from Bottom Brook and Buchans (TL233):

- Reduce export on the Maritime link from 320 MW to 240 MW

BC-13 (Summer Extreme Light)

For the loss of almost any 230 kV line on the Soldiers Pond-Bottom Brook corridor:

- Reduce export on the Maritime link from 320 MW to 240 MW,
- Reduce import on the Island link from 435 MW to 355 MW

For the loss of the largest generator at Bay d'Espoir

- Reduce export on the Maritime link from 320 MW to 240 MW,

BC-14 (Winter Peak)

For the loss of the largest generator at Bay d'Espoir

- Increase import on the Maritime or Island link by 135 MW,

BC-15 (Spring/Fall Peak)

For the loss of the largest generator at Bay d'Espoir

- Reduce export on the Maritime link from 158 MW to 76 MW,

BC-16 (Summer Light)

For the loss of almost any 230 kV line on the Soldiers Pond-Bottom Brook corridor:

- Reduce export on the Maritime link from 500 MW to 250 MW,
- Reduce import on the Island link from 518 MW to 344 MW

BC-17 (Summer Extreme Light)

For the loss of the largest generator at Bay d'Espoir

- Increase import on the Island link from 200 MW to 220 MW,

BC-18 (Winter Peak)

For the loss of the largest generator at Bay d'Espoir

- Reduce export on the Maritime link from 158 MW to 96 MW,

BC-19 (Spring/Fall Peak)

For the loss of almost any 230 kV line on the Soldiers Pond-Bottom Brook corridor:

- Reduce export on the Maritime link from 500 MW to 350 MW,
- Reduce import on the Island link from 814 MW to 664 MW

In summary, during most of the year, the loss of the largest generator on the system (usually Bay d'Espoir #7) will require a reduction in the export on the Maritime link.

During the winter peak load period, line outages do not present a problem in terms of overloads and no adjustment of dc power levels is required.

During the Spring/Fall and Summer periods, because of the reduced ratings of the transmission lines, many transmission line overloads were observed under line outage conditions. These overloads occurred on the Soldiers Pond-Bay d'Espoir corridor and on the Bay d'Espoir-Bottom Brook corridors requiring a reduction in the dc power levels on both links for Soldiers Pond-Bay d'Espoir overloads and on the Maritime link only for Bay d'Espoir-Bottom Brook overloads.

A reduction in the dc power level of the Bottom Brook converter following a loss of generation on the island is relatively straightforward and could be accomplished with a frequency controller that would reduce the dc power level for a drop in frequency. The required reductions following line outages are somewhat more difficult and may need some form of voltage–based controller since many of the outages will be remote from the converter station. The coordination of reductions in the Island link dc power level that will accompany reductions in the Maritime link export for certain line outages is also a difficult control problem for the same reasons. These and other control and reactive power problems will be addressed during the stability studies.

If no reductions are made in the export to Nova Scotia as outlined above, the line overloads that will result on the 230 kV system are summarized in Table 5-1.

Table 5-1: Summary of 230 kV Line Overloads

Load Level	Export to NS	Line Outage			Line Overload			
		From	To	ID	From	To	ID	Loading
Winter Peak	158	Soldiers Pond	Hardwoods	TL242E	Soldiers Pond	Hardwoods	TL201E	107%
Spring/Fall Intermediate	158	Western Avalon	Soldiers Pond	TL217W	Western Avalon	Soldiers Pond	TL201W	116%
Spring/Fall Intermediate	500	Bottom Brook	Massey Drive	TL211	Bottom Brook	Buchans	TL233	115%
		Bottom Brook	Buchans	TL233	Bottom Brook	Massey Drive	TL211	134%
					Massey Drive	Buchans	TL228	146%
		Granite Canal	Bottom Brook	-	Bottom Brook	Massey Drive	TL211	137%
					Bottom Brook	Buchans	TL233	127%
					Massey Drive	Buchans	TL228	151%
					Buchans	Stony Brook	TL205	132%
					Stony Brook	Bay d'Espoir	TL204	101%
					Stony Brook	Bay d'Espoir	TL231	101%
		Massey Drive	Buchans	TL228	Bottom Brook	Buchans	TL233	109%
		Buchans	Stony Brook	TL232	Buchans	Stony Brook	TL205	128%
		Bay d'Espoir	Upper Salmon	TL234	Bottom Brook	Massey Drive	TL211	102%
					Massey Drive	Buchans	TL228	108%
		Western Avalon	Soldiers Pond	TL217W	Western Avalon	Soldiers Pond	TL201W	115%
		Granite Canal	Upper Salmon	TL263	Bottom Brook	Massey Drive	TL211	124%
					Bottom Brook	Buchans	TL233	114%
					Massey Drive	Buchans	TL228	134%
					Buchans	Stony Brook	TL205	118%
Summer Day Light	500	Base Case	-	-	Massey Drive	Buchans	TL228	122%
					Buchans	Stony Brook	TL205	102%
					Western Avalon	Soldiers Pond	TL201W	141%
		Deer Lake	Cat Arm	TL247	Bottom Brook	Buchans	TL233	103%
					Granite Canal	Upper Salmon	TL263	106%
		Deer Lake	Massey Drive	TL248	Bottom Brook	Buchans	TL233	103%
					Granite Canal	Upper Salmon	TL263	103%
		Bottom Brook	Massey Drive	TL211	Bottom Brook	Buchans	TL233	162%
					Granite Canal	Upper Salmon	TL263	123%
		Bottom Brook	Buchans	TL233	Bottom Brook	Massey Drive	TL211	185%
					Granite Canal	Upper Salmon	TL263	131%
		Massey Drive	Buchans	TL228	Bottom Brook	Buchans	TL233	166%
					Granite Canal	Upper Salmon	TL263	123%
		Buchans	Stony Brook	TL205	Buchans	Stony Brook	TL232	137%
					Granite Canal	Upper Salmon	TL263	114%
		Buchans	Stony Brook	TL232	Granite Canal	Upper Salmon	TL263	117%
		Stony Brook	Bay d'Espoir	TL204	Stony Brook	Bay d'Espoir	TL231	139%
					Granite Canal	Upper Salmon	TL263	120%
		Stony Brook	Bay d'Espoir	TL231	Stony Brook	Bay d'Espoir	TL231	139%
					Granite Canal	Upper Salmon	TL263	120%
		Stony Brook	Abitibi Consolidated	TL235	Granite Canal	Upper Salmon	TL263	103%
		Bay d'Espoir	Upper Salmon	TL234	Bottom Brook	Massey Drive	TL211	140%
					Bottom Brook	Buchans	TL233	140%
					Buchans	Stony Brook	TL232	110%
					Stony Brook	Bay d'Espoir	TL204	111%
					Stony Brook	Bay d'Espoir	TL231	111%
		Western Avalon	Come-by-Chance	TL237	Western Avalon	Sunnyside	TL203	120%
		Western Avalon	Soldiers Pond	TL217W	Granite Canal	Upper Salmon	TL263	101%
		Western Avalon	Soldiers Pond	TL201W	Western Avalon	Soldiers Pond	TL217W	138%
					Granite Canal	Upper Salmon	TL263	101%
Summer Night-Extreme Light	320	Bottom Brook	Buchans	TL233	Bottom Brook	Massey Drive	TL211	114%
					Massey Drive	Buchans	TL228	124%
		Bottom Brook	Granite Canal	-	Bottom Brook	Massey Drive	TL211	104%
					Massey Drive	Buchans	TL228	106%
		Buchans	Stony Brook	TL232	Buchans	Stony Brook	TL205	106%
		Western Avalon	Soldiers Pond	TL217W	Western Avalon	Soldiers Pond	TL201W	140%

5.3 ISLAND LINK MAIN PARAMETERS

The major parameters for the Island link are shown in the following table:

Table 5-2: Island Link Major Parameters

Parameter	Muskrat Falls		Soldiers Pond	
	Normal	**Overload**	**Normal**	**Overload**
System AC Bus Voltage (kVrms)	315	315	230	230
DC Voltage(kV)	±350	±350	±317	±269
DC Current (A)	1,286	1,929	1,286	1,929
DC Power (MW)	900	675	814	519
Firing/Margin Angle (degrees)	15	15	18	18
Converter Transformer Rating (MVA/pole)	523	785	481	613
Converter AC Bus Voltage (kV)	288	288	265	225

Note: Overload values assume mono-polar operation with ground return.

The above values are preliminary only and will be finalized during the design stage.

5.4 MARITIME LINK

The major parameters for the Maritime link are shown in the following table:

Table 5-3: Maritime Link Major Parameters

Parameter	Bottom Brook	Nova Scotia
	Normal	**Normal**
System AC Bus Voltage (kVrms)	230	230
DC Voltage(kV)	±200	±194
DC Current (A)	1,250	1,250
DC Power (MW)	500	484
Firing/Margin Angle (degrees)	15	18
Converter Transformer Rating (MVA/pole)	291	286
Converter AC Bus Voltage (kV)	164	162

Note: The above values are preliminary only and will be finalized during the design stage.

5.5 REACTIVE COMPENSATION REQUIREMENTS

The reactive support required at each converter station was examined for normal and outage conditions for each scenario.

For the Muskrat Falls converter station, no additional reactive support was required other than the 220 MVAr assumed for the harmonic filters associated with the converter station.

For the Soldiers Pond converter station, up to 240 MVAr of reactive support was required when importing the rated capacity of the Island link (900 MW at the rectifier, 814 MW at the inverter). This level of support was based on one of the three synchronous condensers at Holyrood being out of service.

For the Bottom Brook converter, provided reductions in the export to Nova Scotia can be made in the event of a line outage, reactive compensation over the range of +320/-100 MVAr was required. The application of VSC technology may well be appropriate at this location, given its inherent reactive control capability and the fact that the major portion of the link is composed of submarine cable.

5.6 SHORT-CIRCUIT LEVELS

Under maximum generation conditions, the following table shows the maximum short-circuit level at each converter bus and the highest value of fault level on the island 230 kV and 138 kV system.

Table 5-4: Maximum Fault Levels

Station	kV	Three-phase		Single-phase	
		kA	MVA	kA	MVA
Muskrat Falls	315	6.2	3,400	8.0	4,350
Soldiers Pond	230	6.1	2,425	7.5	3,000
Bottom Brook	230	3.8	1,525	3.9	1,550
Bay d’Espoir	230	9.6	3,850	11.5	4,600
Stony Brook	138	5.9	1,400	7.3	1,730

It can be seen that none of the above fault levels are excessive and are all well within typical switchgear fault-interrupting capabilities. The higher single-phase fault levels are due to the presence of a number of transformers (system and generator transformers) at the locations considered.

The following table shows the same case with all machines at Holyrood connected and with 2x150 MVA synchronous condensers at Soldiers Pond.

Table 5-5: Maximum Fault Levels with SC at SPD

Station	kV	Three-phase		Single-phase	
		kA	MVA	kA	MVA
Muskrat Falls	315	6.2	3,400	8.0	4,350
Soldiers Pond	230	7.4	2,960	8.8	3,510
Bottom Brook	230	3.8	1,525	3.9	1,550
Bay d'Espoir	230	9.8	3,920	11.7	4,670
Stony Brook	138	5.9	1,410	7.3	1,740

The inclusion of the disconnected machine at Holyrood and the addition of the two synchronous condensers only affected the short-circuit level at Soldiers Pond. The short-circuit current increased by approximately 1.3 kA.

The following table shows the minimum effective short-circuit ratio (ESCR) and the corresponding converter MW and 3-phase fault level for the specific scenarios considered under normal conditions with all equipment in service.

Table 5-6: Minimum ESCR/Fault Levels-System Normal

Station	Converter MW	Min.Fault Level MVA	ESCR
Muskrat Falls	900	3,390	3.52
Soldiers Pond	814	2,310	2.52
Bottom Brook	500	1,345	2.44

Under line outage conditions on the ac system, the short circuit level is decreased and the following fault level and short-circuit ratios will apply.

Table 5-7: Minimum ESCR/Fault Levels-Outage Conditions

Station	Converter MW	Disconnected Line	Min.Fault Level MVA	ESCR
Muskrat Falls	900	CHF-MFA	2,730	2.78
Soldiers Pond	814	SPD-WAV (TL217W)	2,190	2.38
Bottom Brook	500	BBK-MDR (TL211)	905	1.56

While the ESCR at Muskrat Falls remained above the normally accepted minimum value of 2.5, the value at Soldiers Pond was marginally below 2.5 and the value at Bottom Brook was less than 2.0. These values suggest that while the Muskrat Falls converter should experience no particular difficulties in recovering from ac system disturbances, the Soldiers Pond converter may need some additional support in terms of reactive power and/or inertia and the Bottom Brook converter will almost certainly need special consideration in terms of location, additional support and/or the application of VSC technology.

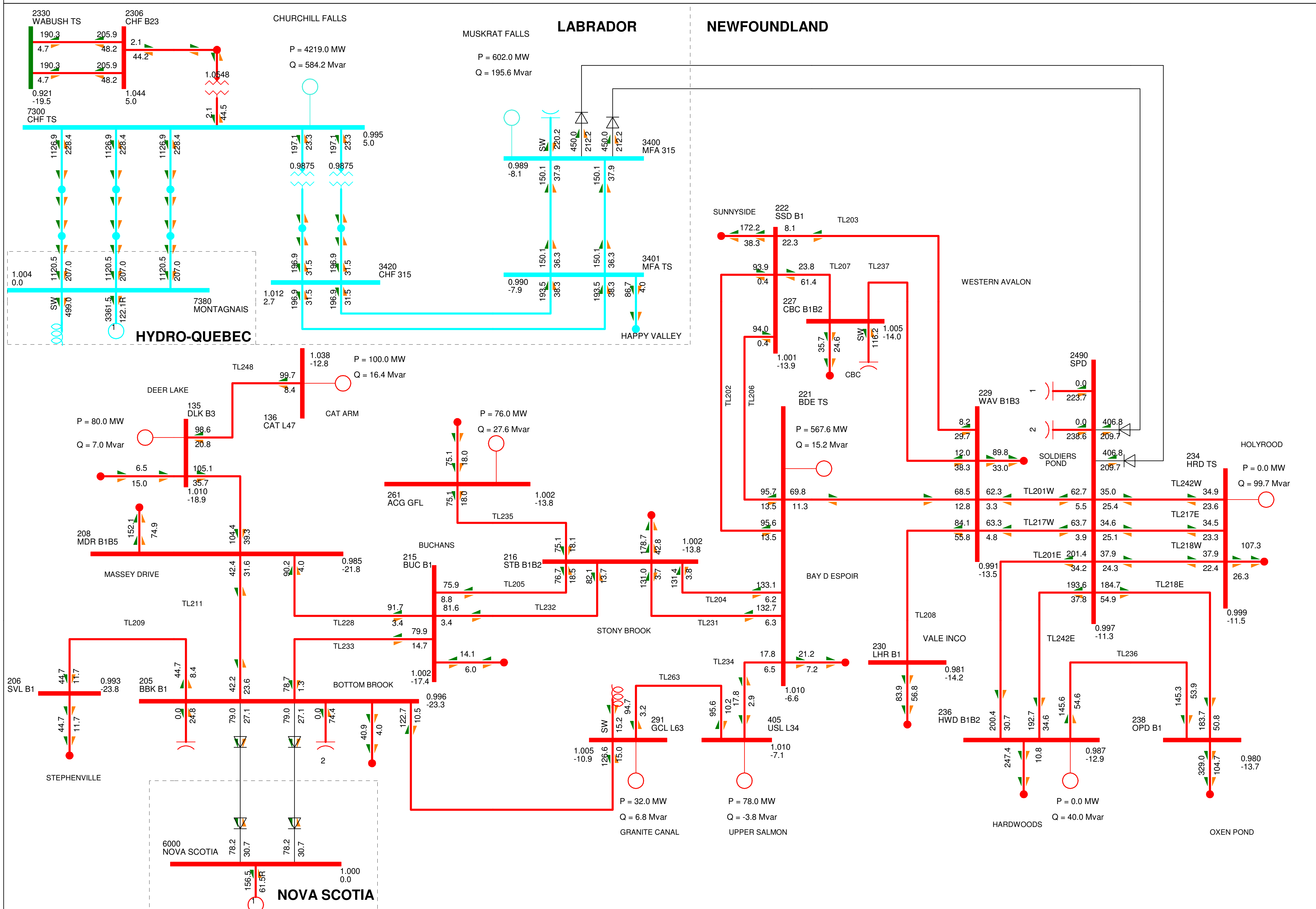
APPENDIX-A
BASE CASE LOAD FLOW PLOTS

LIST OF FIGURES

Attachment A- 1

BC-1 Peak 2017/Island Link 814MW/Maritime Link 158MW/Economic Dispatch

BC1 - WINTER PEAK 2017, 1552 MW, 814 MW IMPORT AND 158 MW EXPORT



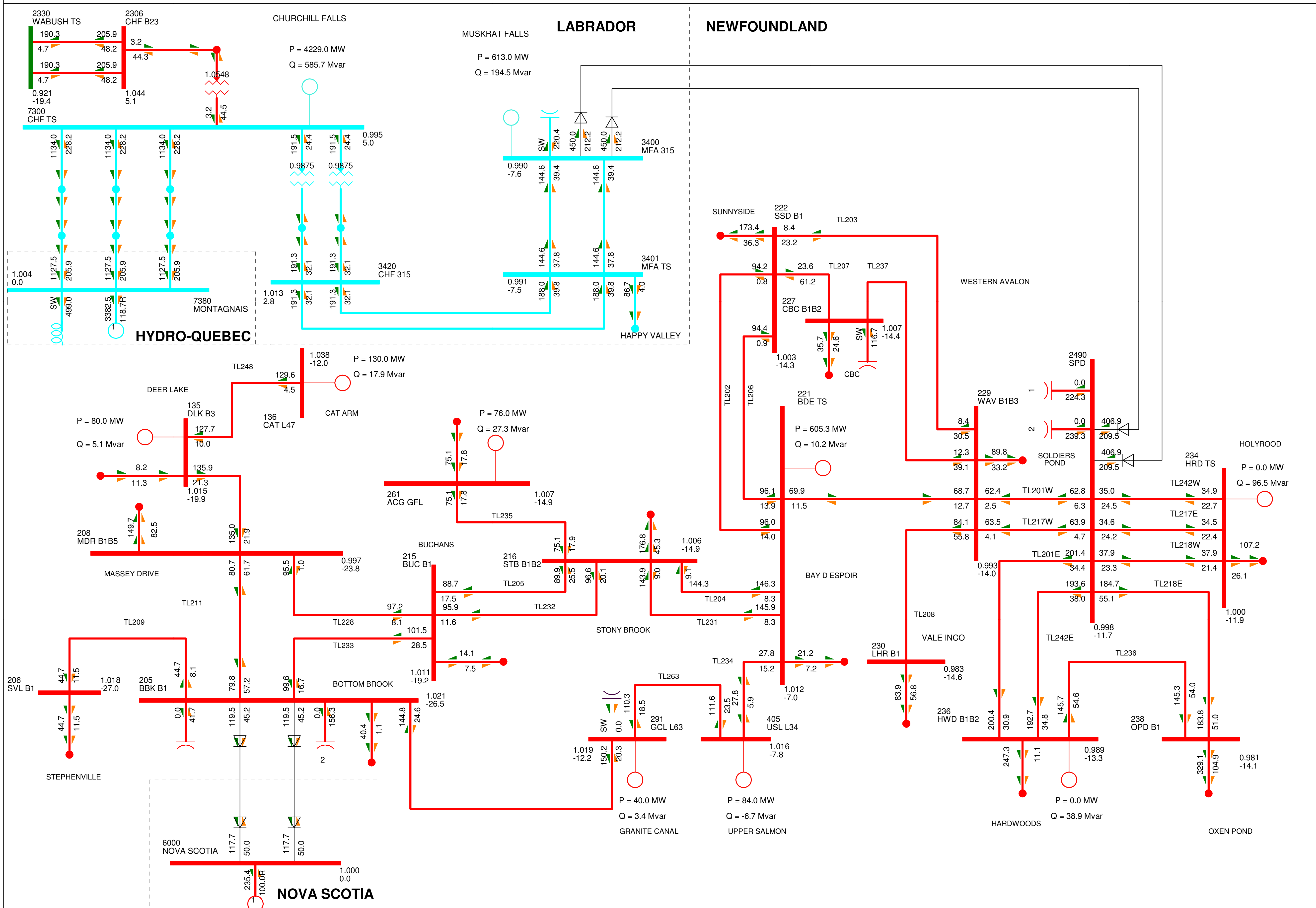
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 2

BC-2 Peak 2017/Island Link 814MW/Maritime Link 239 MW/Maximum Dispatch

BC2 - WINTER PEAK 2017, 1552 MW, 814 MW IMPORT AND 239 MW EXPORT



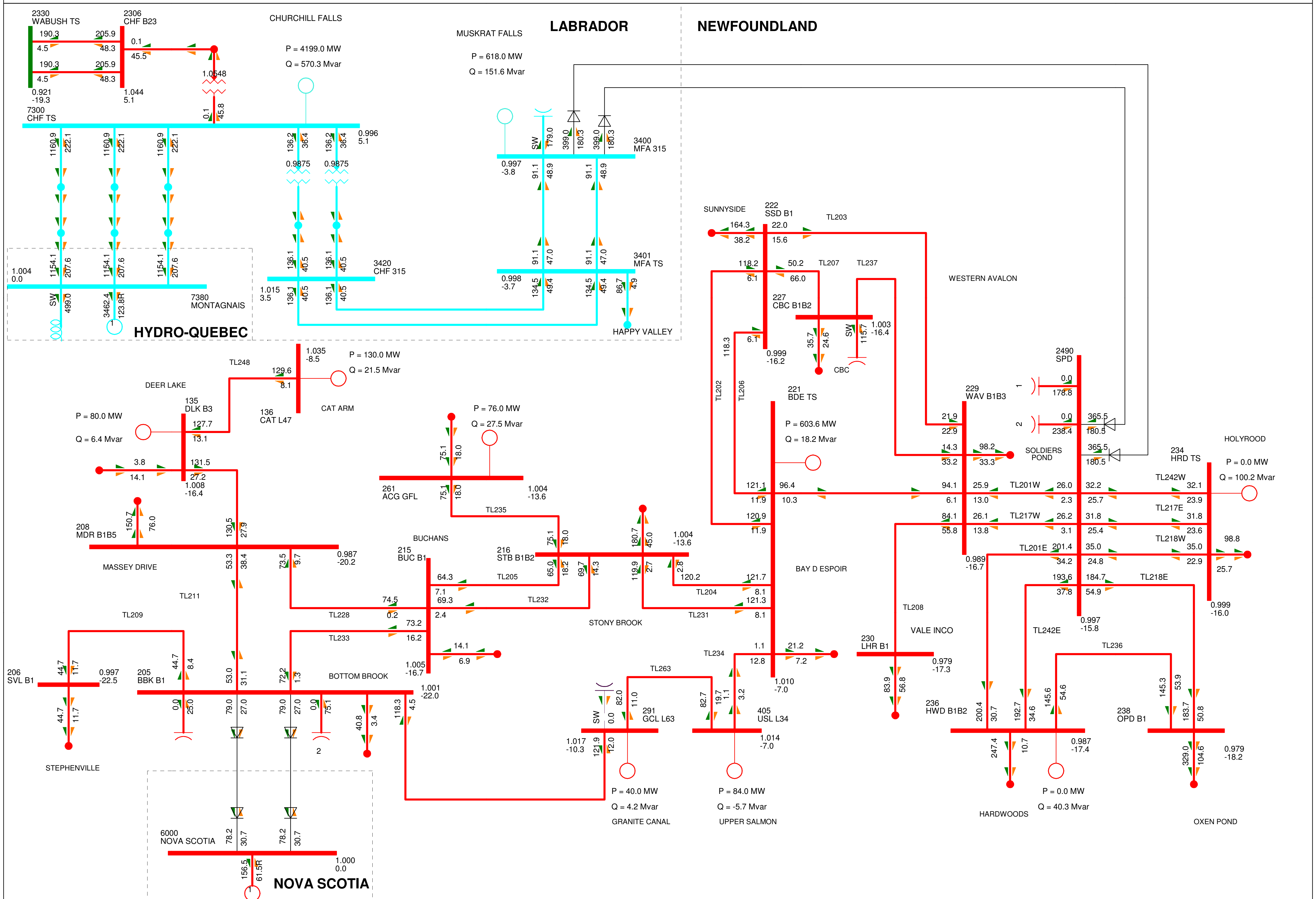
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Maximum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 3

BC-3 Peak 2017/Island Link 730MW/Maritime Link 158MW/Maximum Dispatch

BC3 - WINTER PEAK 2017, 1552 MW, 730 MW IMPORT AND 158 MW EXPORT



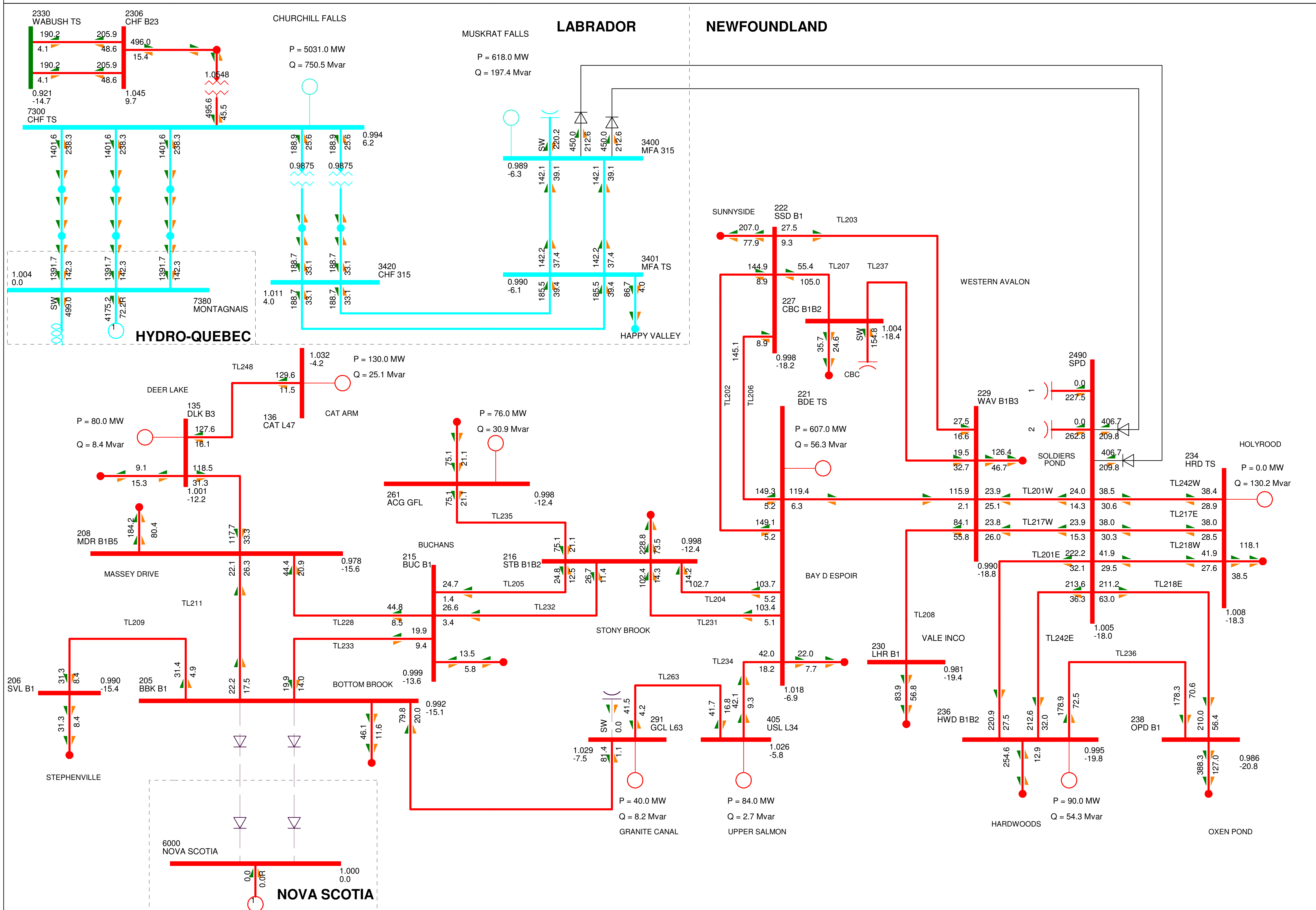
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Maximum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 4

BC-4 Peak 2041/Island Link 814MW/Maritime Link 0MW/Maximum Dispatch

BC4 - FUTURE PEAK 2041, 1900 MW, 814 MW IMPORT AND 0 MW EXPORT



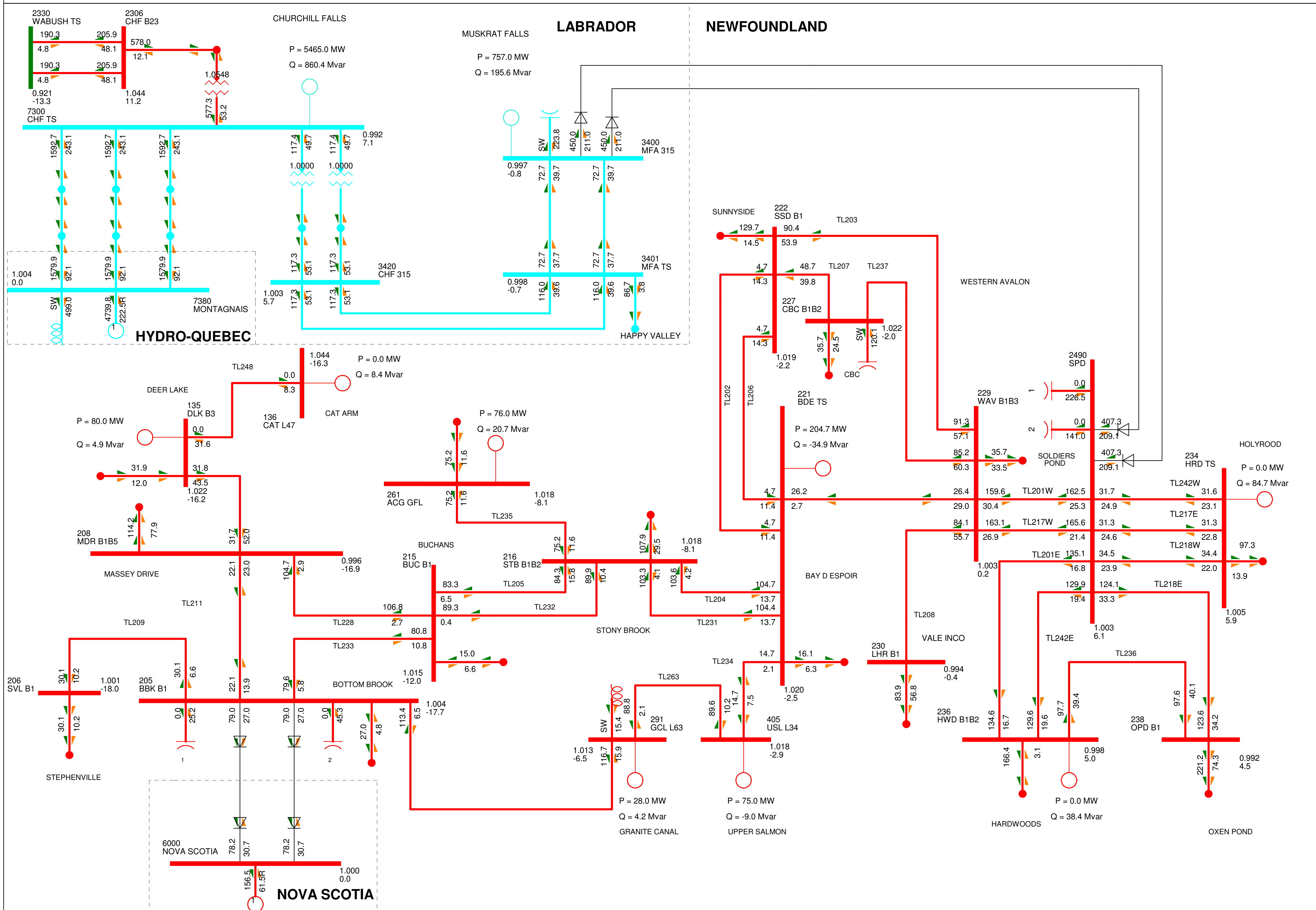
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Maximum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 5

BC-5 Intermediate 2017/Island Link 814MW/Maritime Link 158MW/Economic Dispatch

BC5 - SPRING/FALL INTERMEDIATE 2017, 1100 MW, 814 MW IMPORT AND 158 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

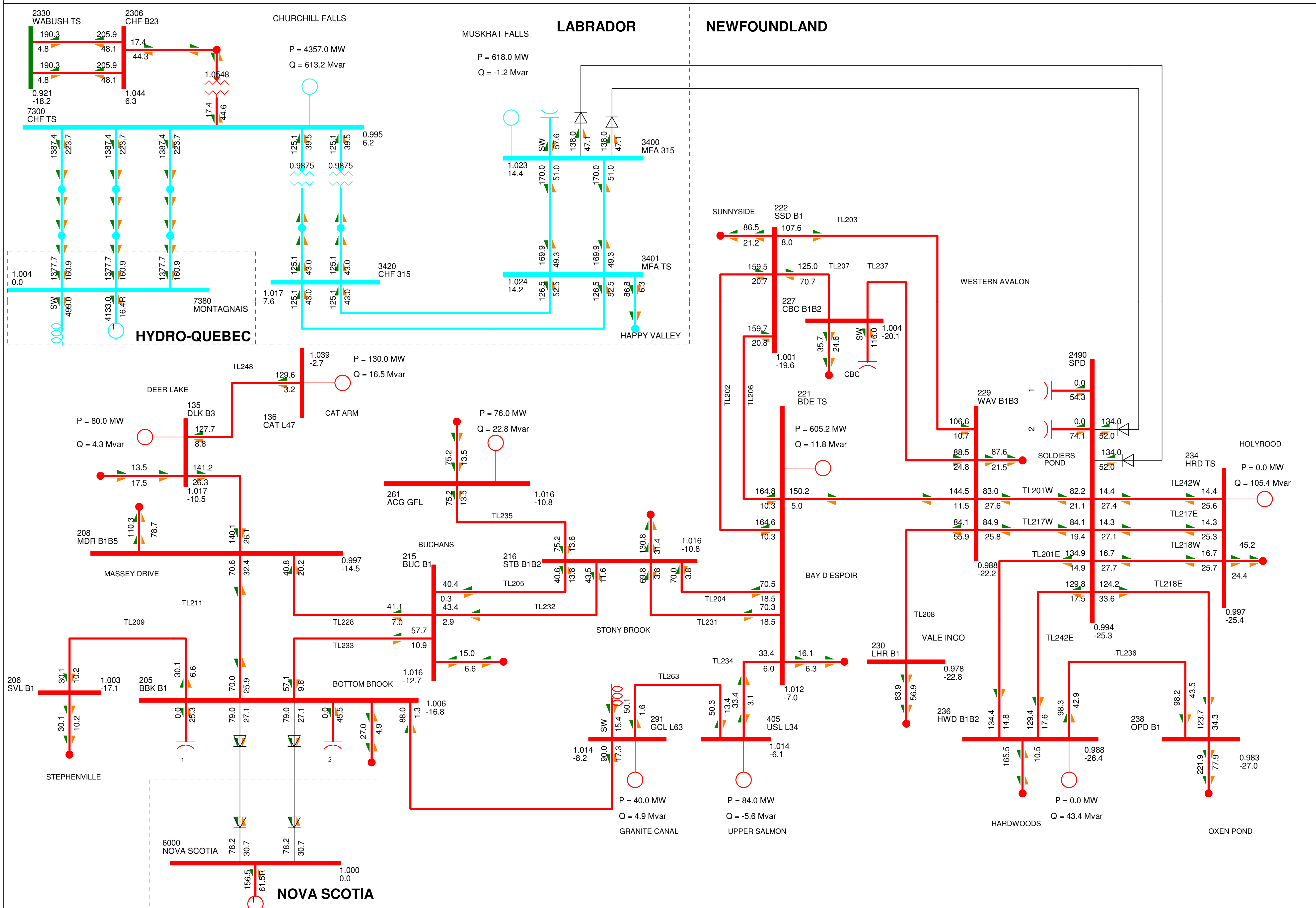
100.0%RATEB
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 6

BC-6 Intermediate 2017/Island Link 268MW/Maritime Link 158MW/Maximum Dispatch

BC6 - SPRING/FALL INTERMEDIATE 2017, 1100 MW, 268 MW IMPORT AND 158 MW EXPORT

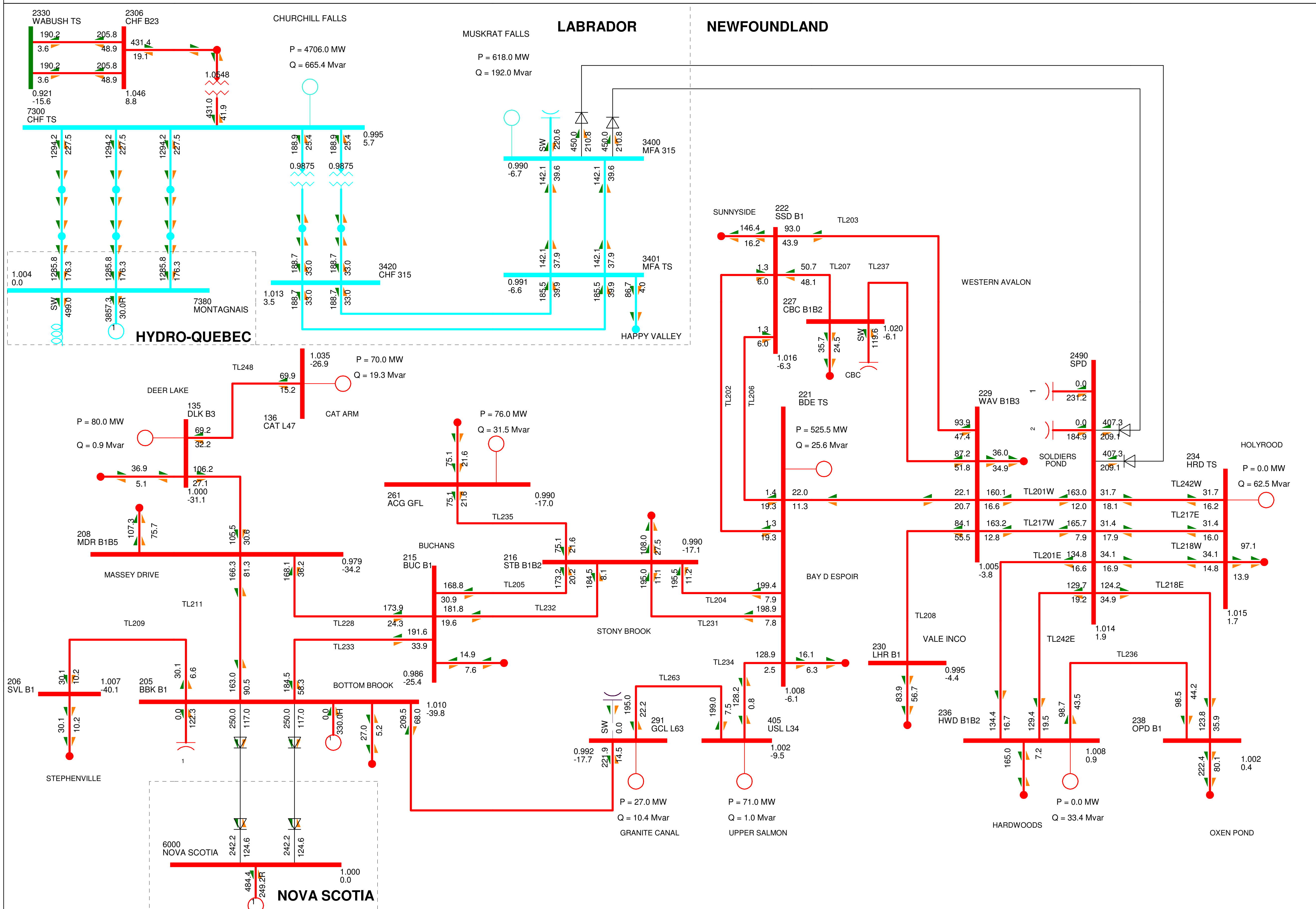


Bus - VOLTAGE (PU)/ANGLE Branch - MW/Mvar Equipment - MW/Mvar 100.0%RATEB 1.050OV 0.950UV kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000	- Base Case - Generation: Maximum	- Bipolar operation of Island HVDC - Bipolar operation of Maritime HVDC

Attachment A- 7

BC-7 Intermediate 2017/Island Link 814MW/Maritime Link 500MW/Economic Dispatch

BC7 - SPRING/FALL INTERMEDIATE 2017, 1100 MW, 814 MW IMPORT AND 500 MW EXPORT



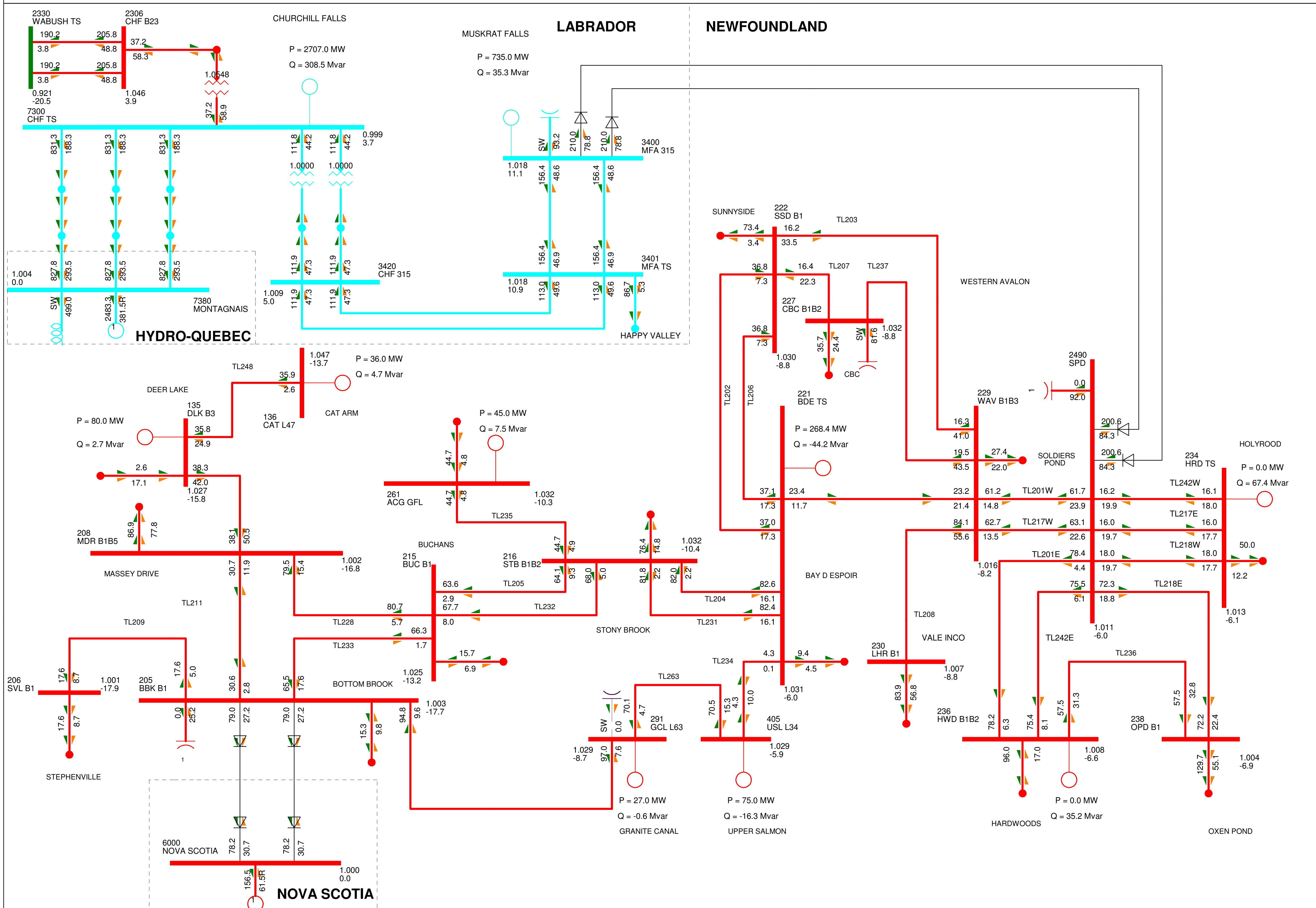
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEB
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 8

BC-8 Light 2017/Island Link 400MW/Maritime Link 158MW/Minimum Dispatch

BC8 - SUMMER DAY LIGHT 2017, 700 MW, 400 MW IMPORT AND 158 MW EXPORT



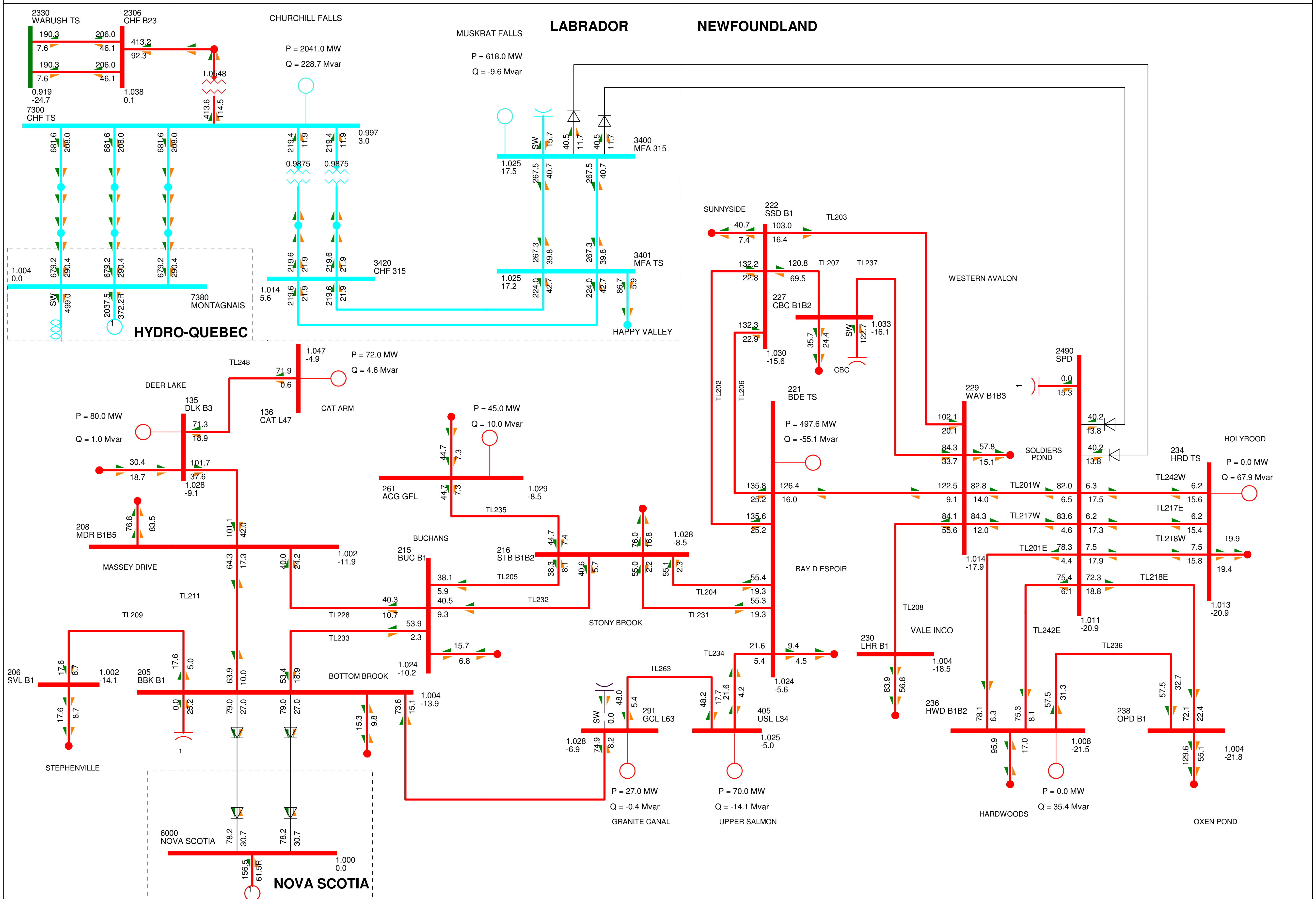
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000>230.000

- Base Case
- Generation: Minimum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 9

BC-9 Light 2017/Island Link 80MW/Maritime Link 158MW/Economic Dispatch

BC9 - SUMMER DAY LIGHT 2017, 700 MW, 80 MW IMPORT AND 158 MW EXPORT



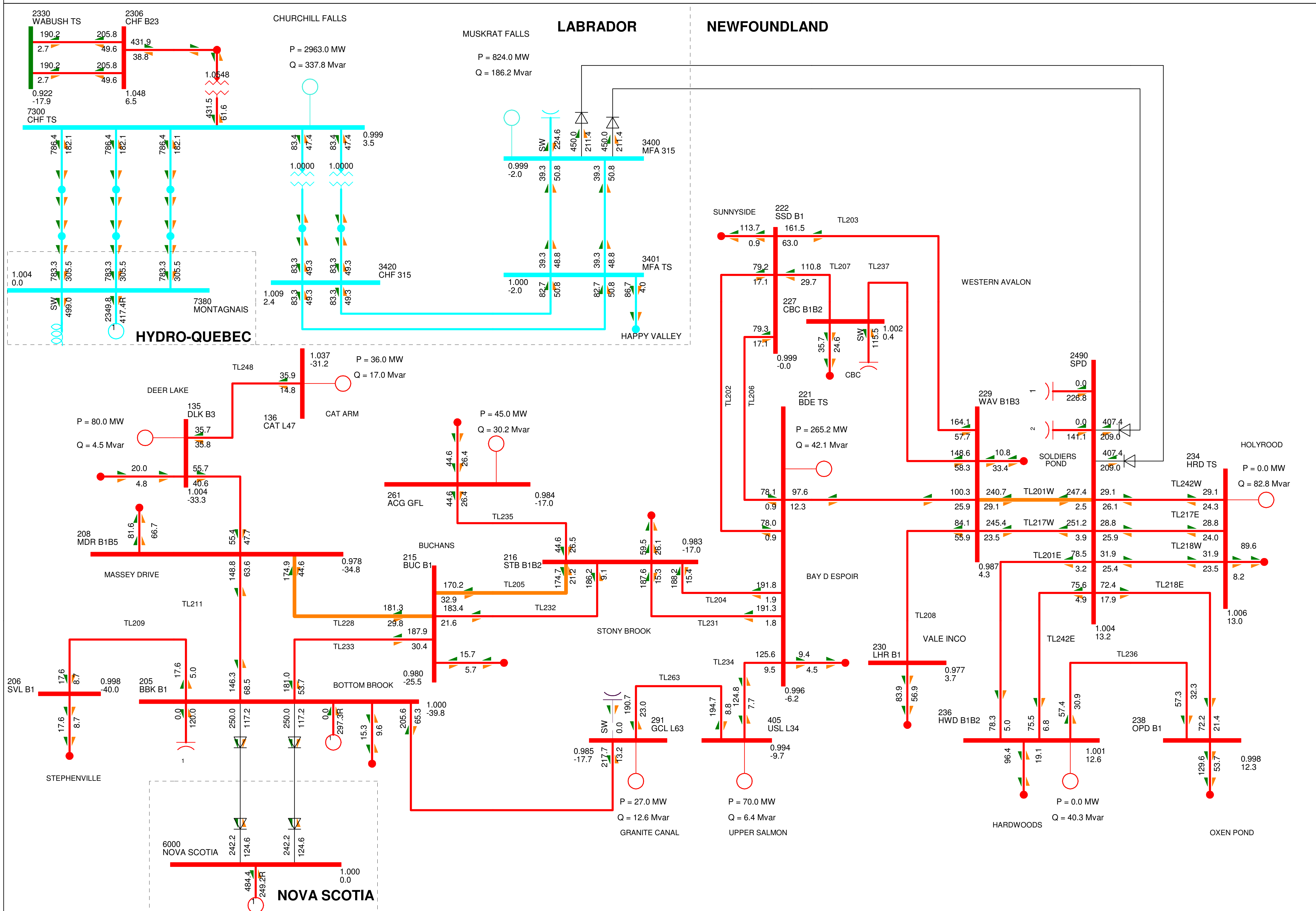
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000>230.000

- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 10

BC-10 Light 2017/Island Link 814MW/Maritime Link 500MW/Economic Dispatch

BC10 - SUMMER DAY LIGHT 2017, 700 MW, 814 MW IMPORT AND 500 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

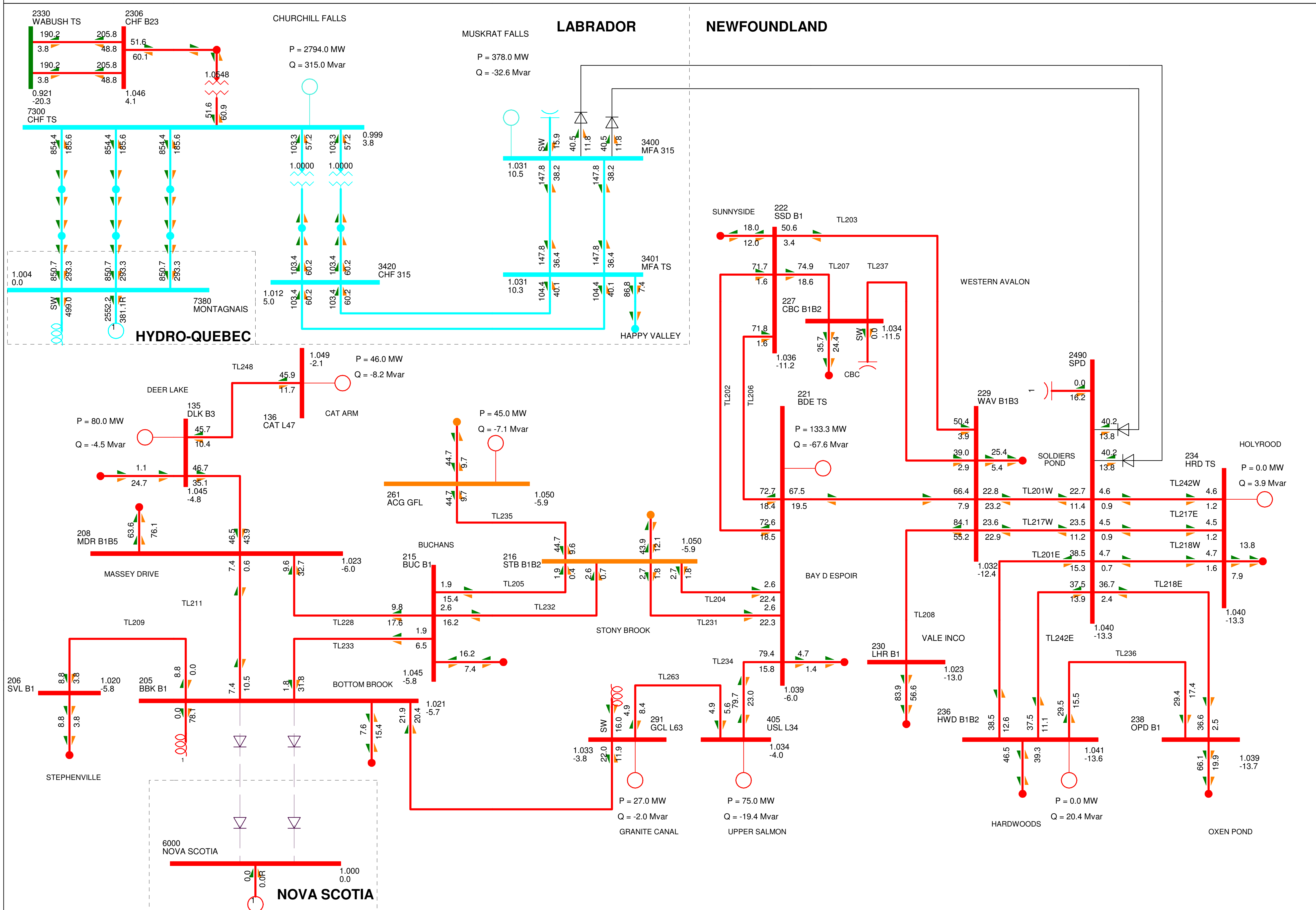
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000>230.000

- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 11

BC-11 Extreme Light 2017/Island Link 80MW/Maritime Link 0MW/Economic Dispatch

BC11 - SUMMER NIGHT EXTREME LIGHT 2017, 420 MW, 80 MW IMPORT AND 0 MW EXPORT



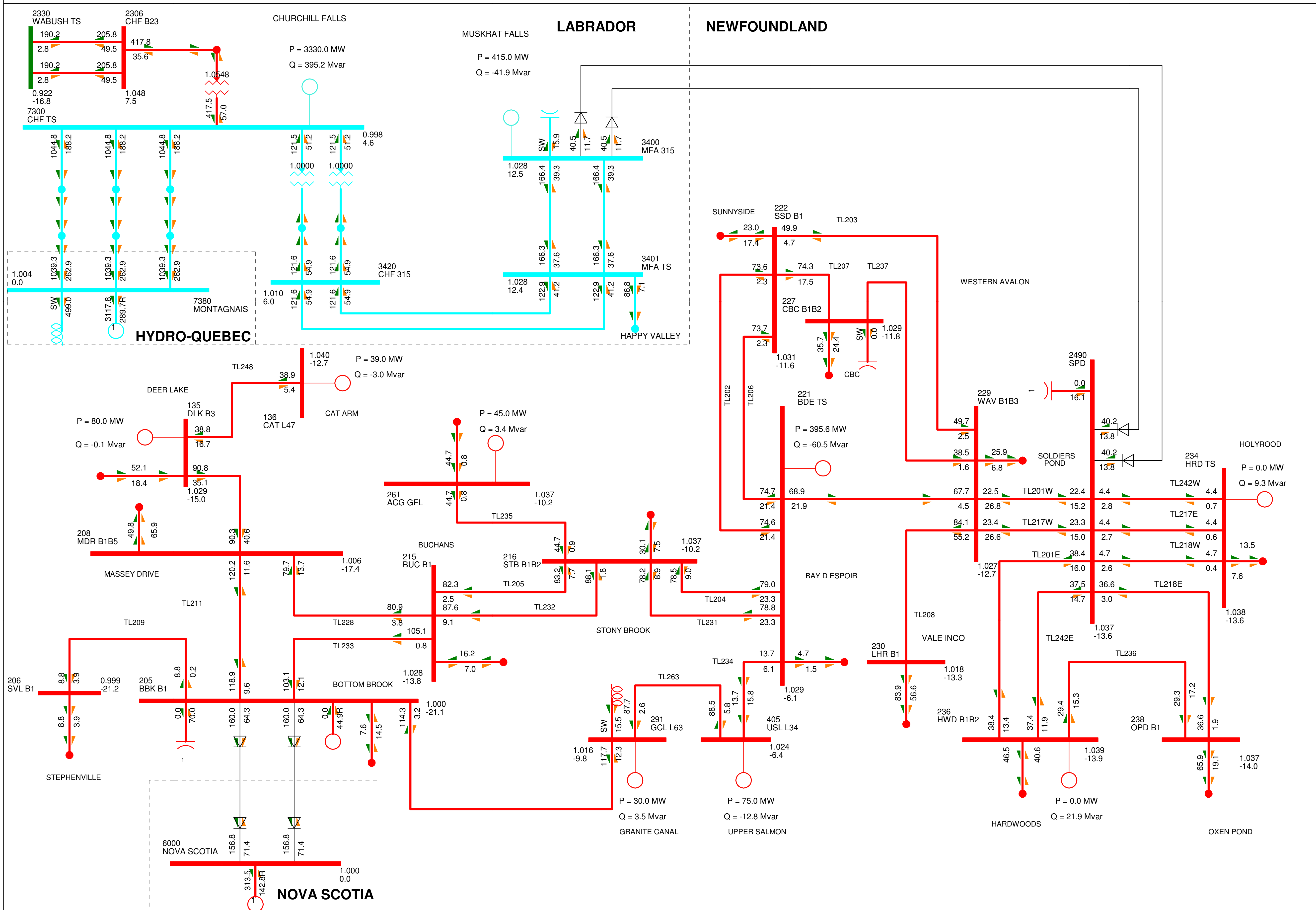
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 12

BC-12 Extreme Light 2017/Island Link 80MW/Maritime Link 320MW/Economic Dispatch

BC12 - SUMMER NIGHT EXTREME LIGHT 2017, 420 MW, 80 MW IMPORT AND 320 MW EXPORT



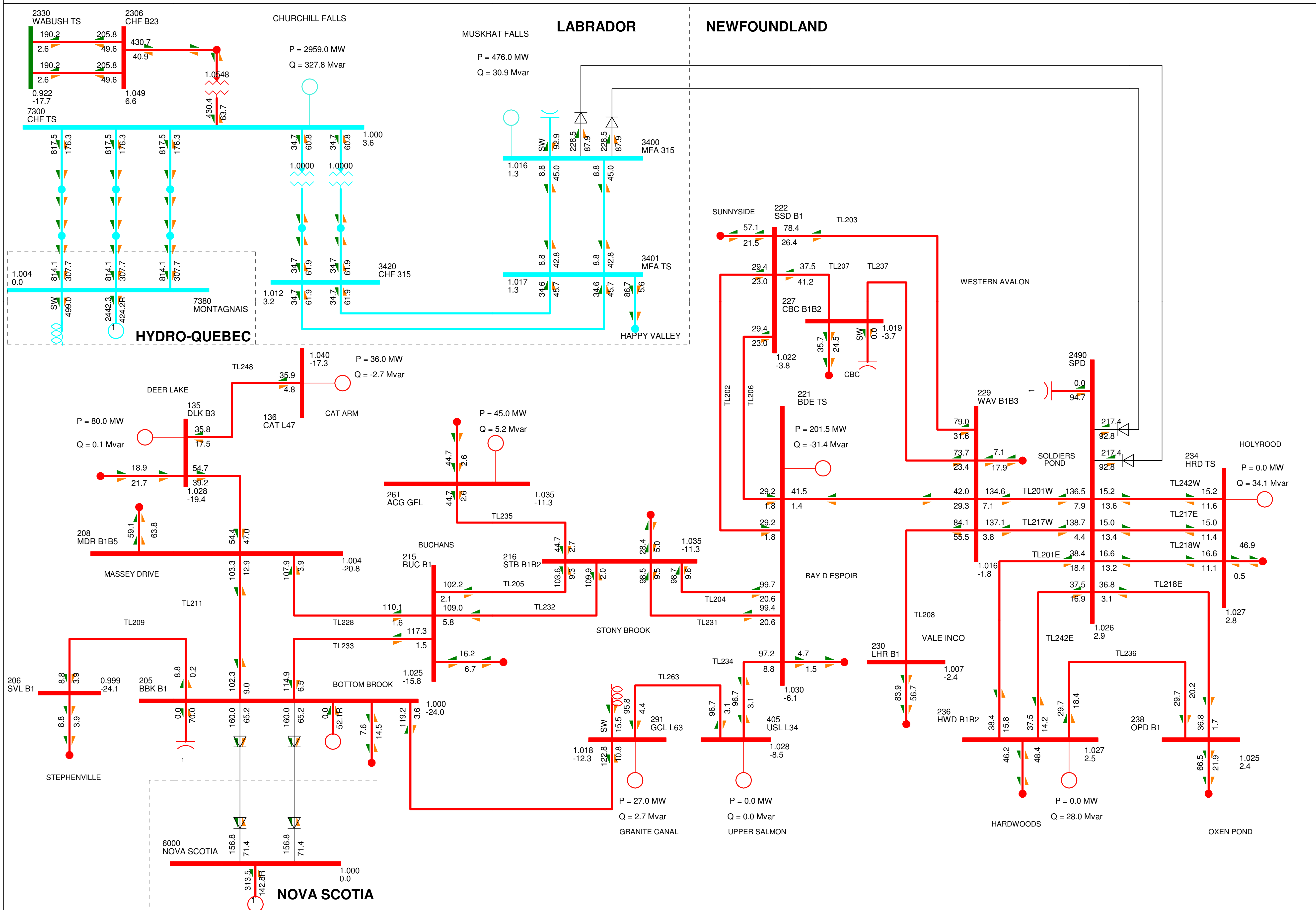
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic Dispatch
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 13

BC-13 Extreme Light 2017/Island Link 435MW/Maritime Link 320MW/Minimum Dispatch

BC13 - SUMMER NIGHT EXTREME LIGHT 2017, 420 MW, 435 MW IMPORT AND 320 MW EXPORT



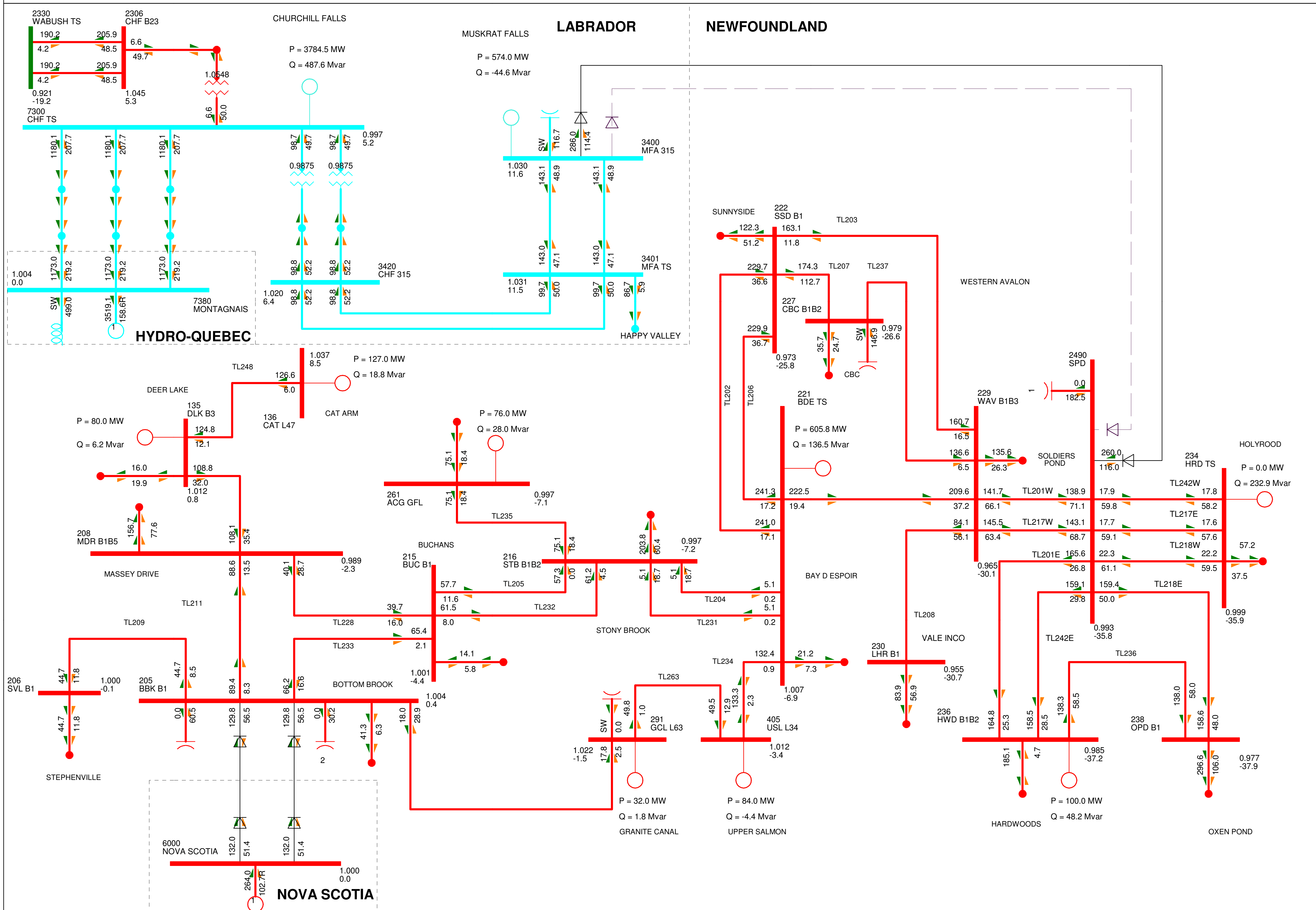
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000<=230.000 >230.000

- Base Case
- Generation: Minimum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 14

BC-14 Peak 2017/Island Link 260MW-Monopole/Maritime Link -260MW/ Maximum Dispatch

BC14 - WINTER PEAK 2017, 1552 MW, 260 MW IMPORT (LAB) AND 260 MW IMPORT (NS)



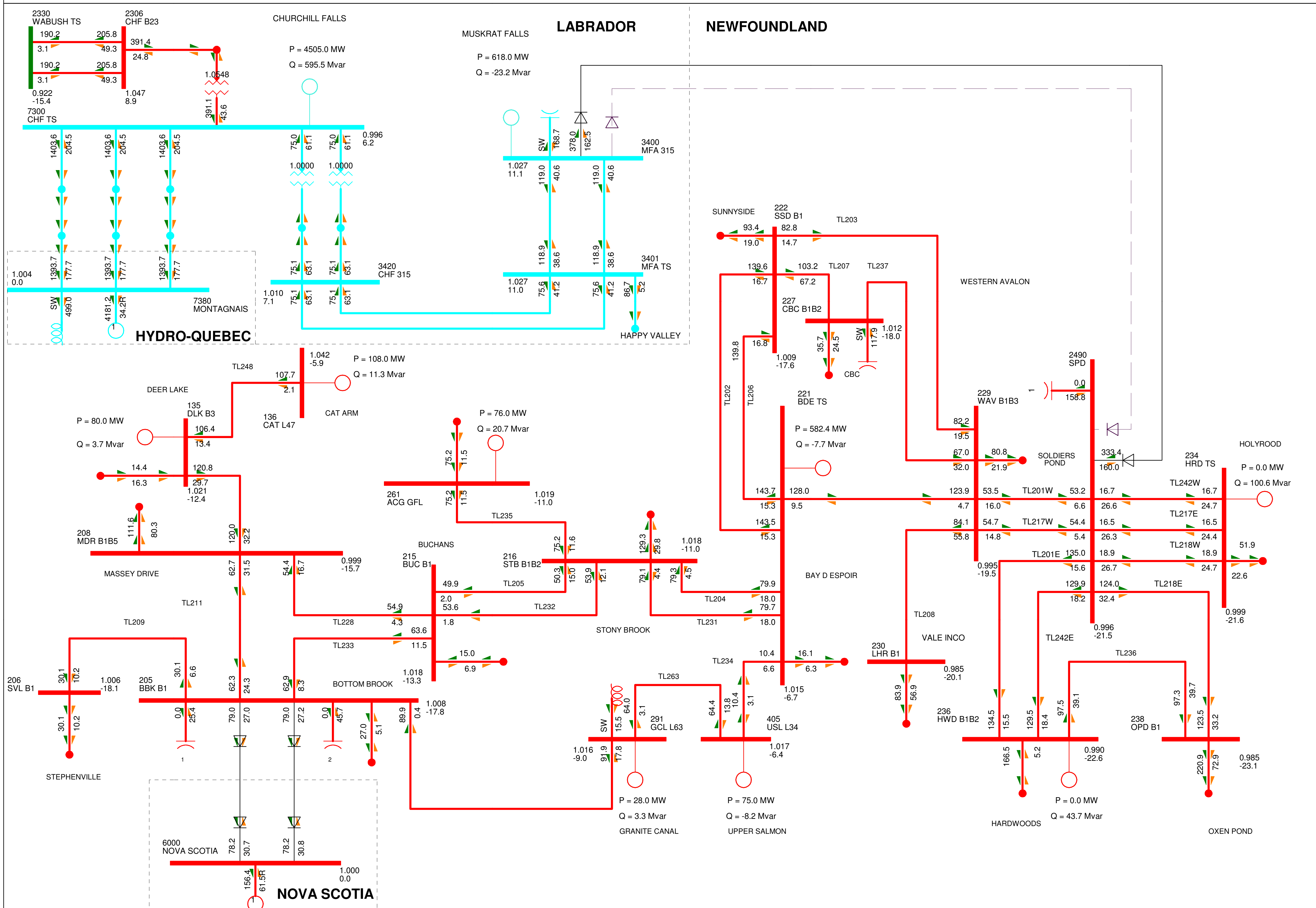
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Maximum
- Monopolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 15

BC-15 Intermediate 2017/Island Link 333MW-Monopole/Maritime Link 158MW/Economic Dispatch

BC15 - SPRING/FALL INTERMEDIATE 2017, 1100 MW, 333 MW IMPORT AND 158 MW EXPORT



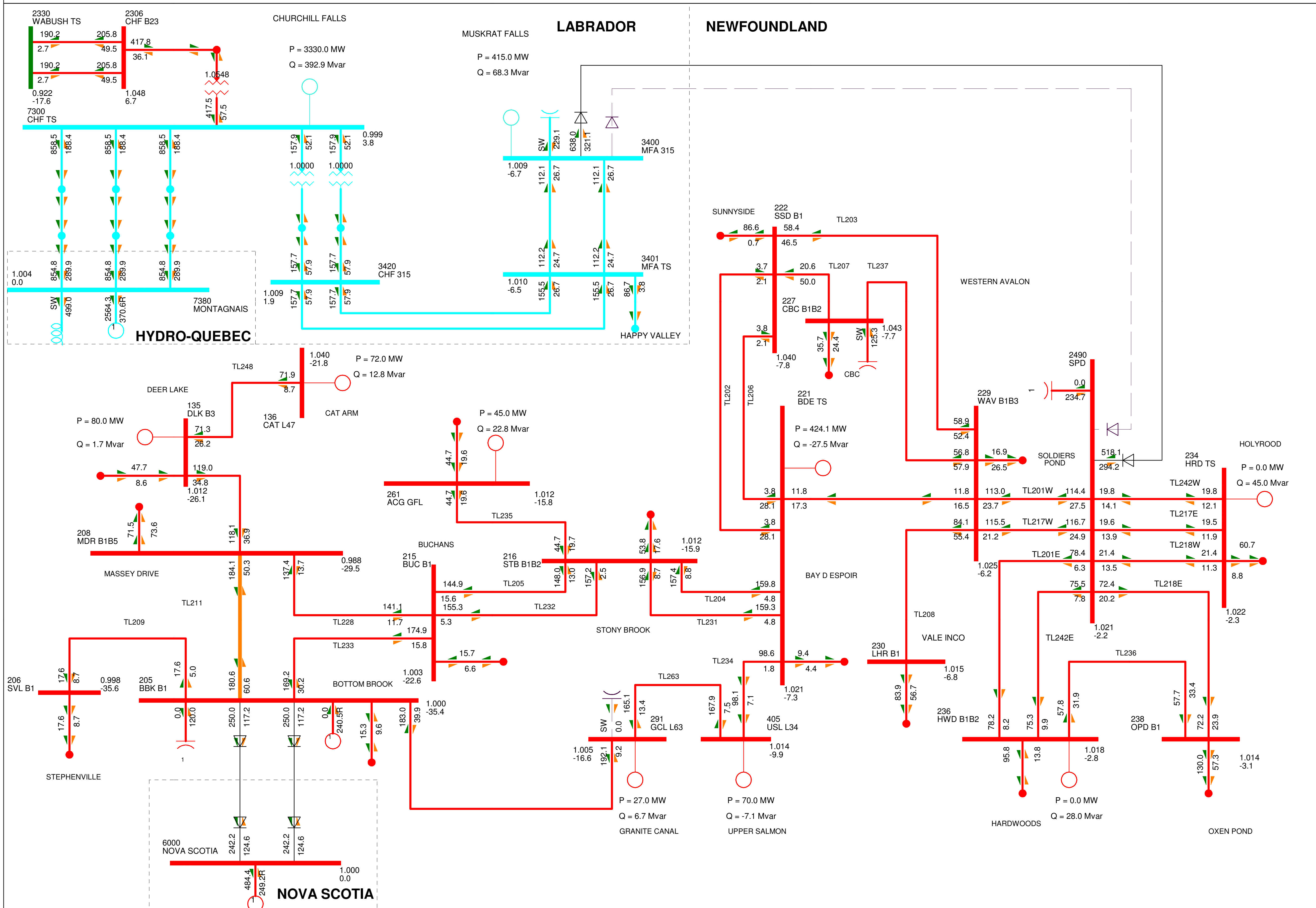
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEB
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic Dispatch
- Monopolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 16

BC-16 Light 2017/Island Link 518MW-Monopole/Maritime Link 500MW/ Minimum Dispatch

BC16 - SUMMER DAY LIGHT 2017, 700 MW, 518 MW IMPORT AND 500 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar

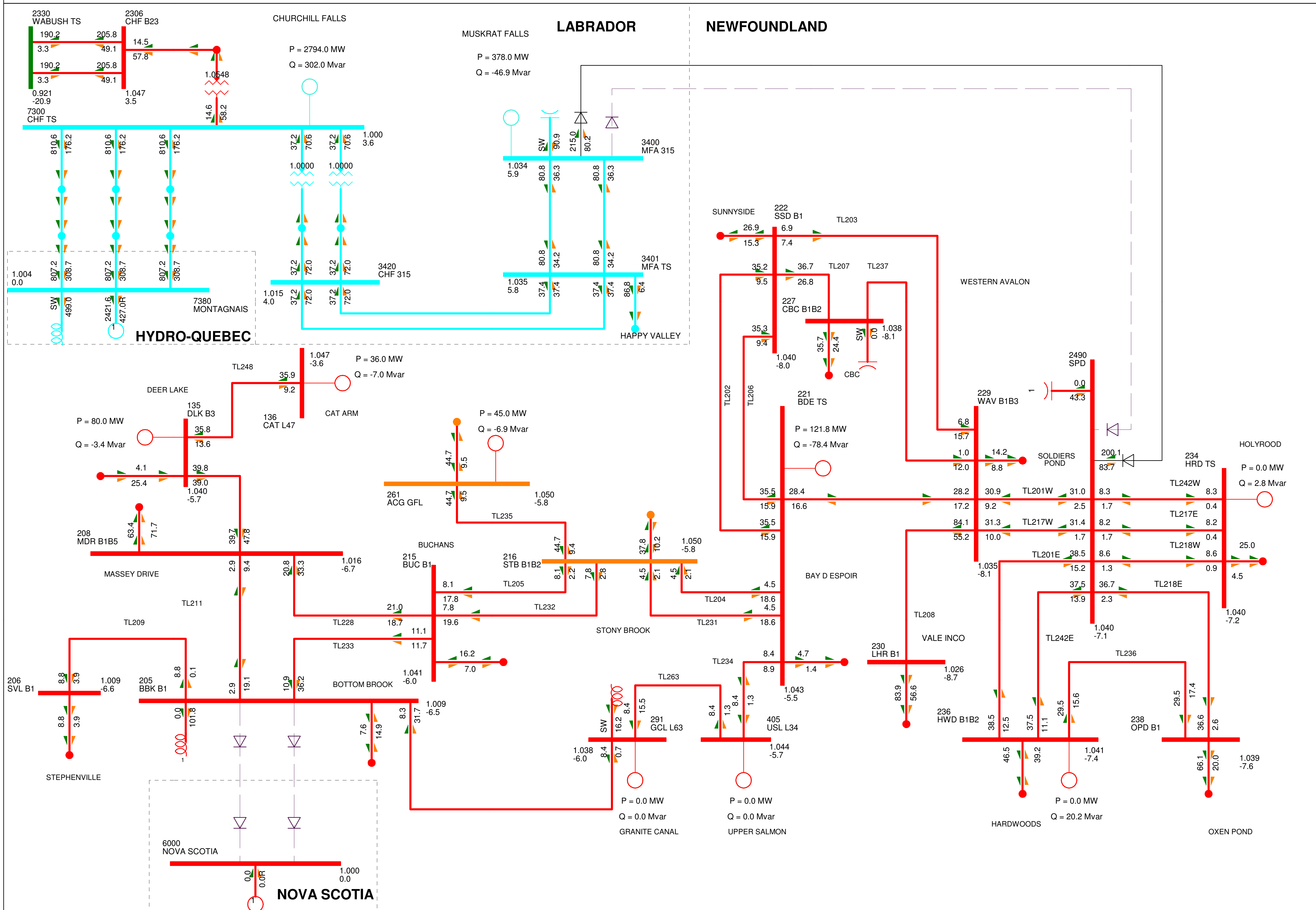
100.0%RATEA
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000>230.000

- Base Case
- Generation: Minimum
- Monopolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 17

BC-17 Extreme Light 2017/Island Link 200MW-Monopole/Maritime Link 0MW/ Minimum Dispatch

BC17 - SUMMER NIGHT EXTREME LIGHT 2017, 420 MW, 200 MW IMPORT AND 0 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEA

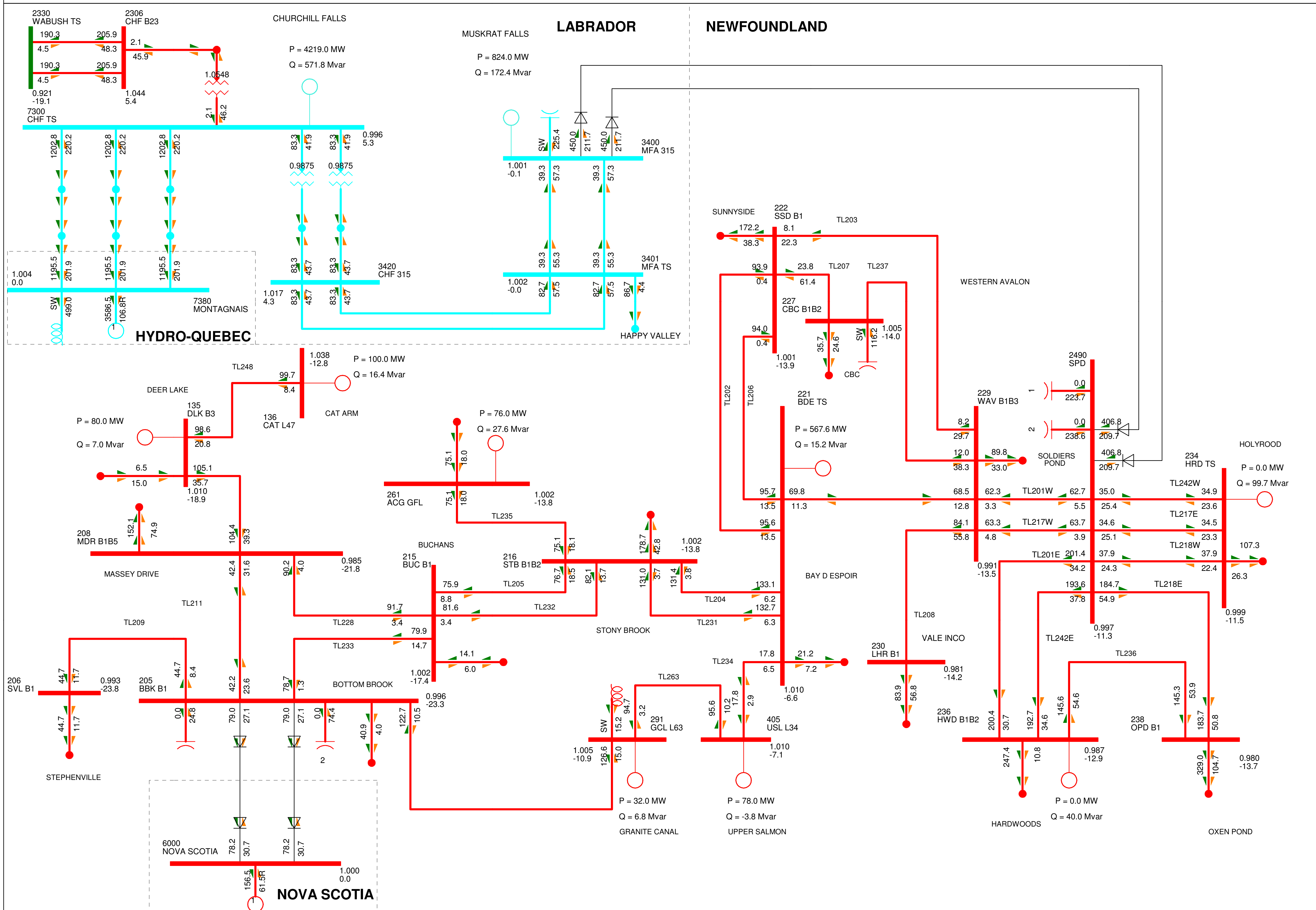
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Minimum
- Monopolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 18

BC-18 Peak 2017/Island Link 814MW/Maritime Link 158MW/Economic Dispatch (4 units @Muskrat Falls)

BC18 - WINTER PEAK 2017, 1552 MW, 814 MW IMPORT AND 158 MW EXPORT



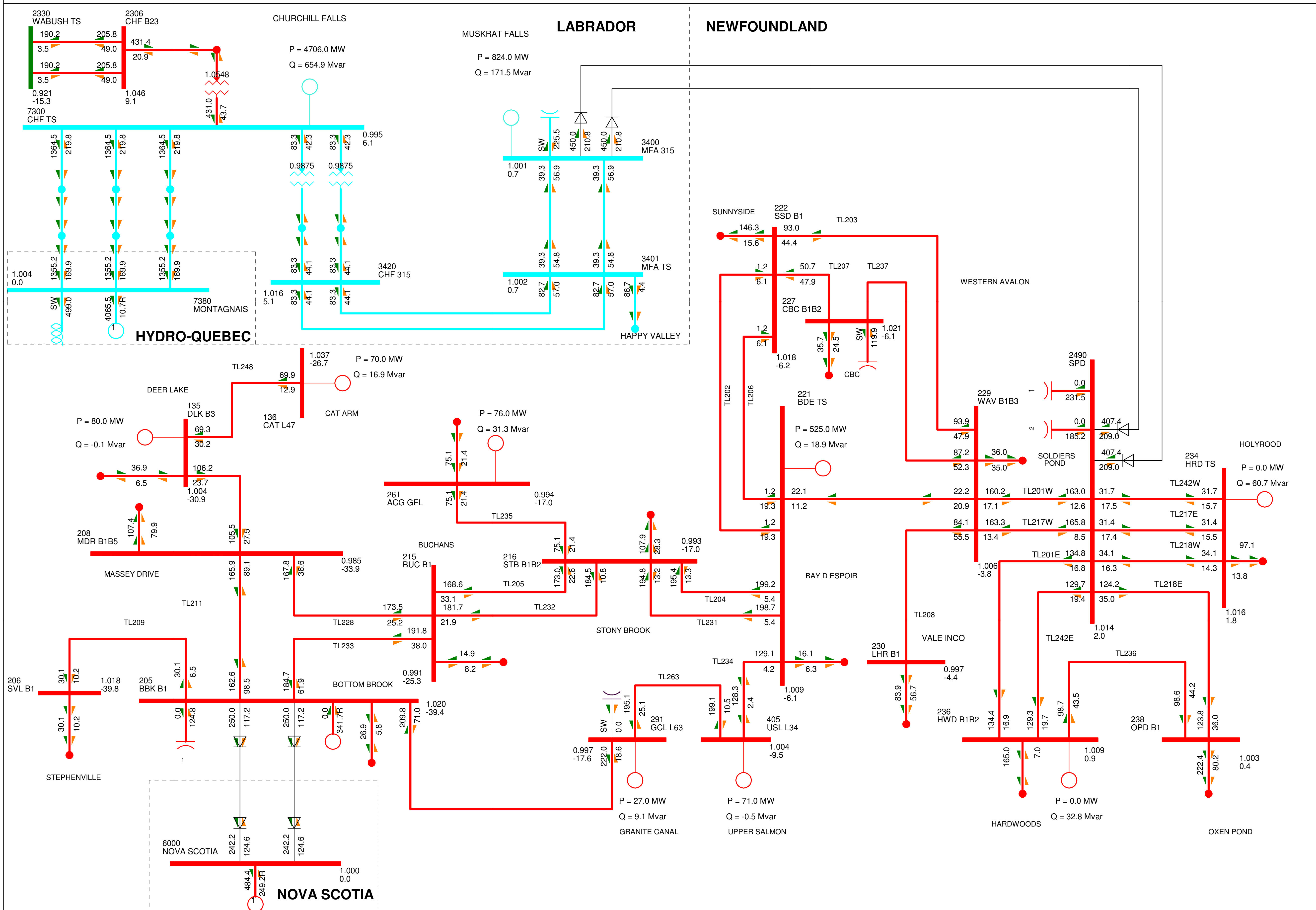
Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEC
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic dispatch
- Muskrat Falls Generation: Maximum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

Attachment A- 19

BC-19 Intermediate 2017/Island Link 814MW/Maritime Link 500MW/Economic Dispatch (4 units @Muskrat Falls)

BC19 - SPRING/FALL INTERMEDIATE 2017, 1100 MW, 814 MW IMPORT AND 500 MW EXPORT



Bus - VOLTAGE (PU)/ANGLE
Branch - MW/Mvar
Equipment - MW/Mvar
100.0%RATEB
1.050OV 0.950UV
kV: <=6.900 <=16.000 <=25.000 <=46.000 <=69.000 <=138.000 <=230.000 >230.000

- Base Case
- Generation: Economic Dispatch
- Muskrat Falls Generation: Maximum
- Bipolar operation of Island HVDC
- Bipolar operation of Maritime HVDC

SNC·LAVALIN

nalcor energy

Lower Churchill Project

HVdc SYSTEM MODES OF OPERATION AND CONTROL STRATEGIES STUDY

SLI Document No.: 505573-480A-47ER-0005-01

Nalcor Reference No.: ILK-SN-CD-8000-EL-SY-0003-01–B2

Date: 17-Apr-2012

Prepared by: For Rao Atmuri

Verified by: For Peter Anderson

Approved by: Satish Sud

REGISTERED PROFESSIONAL ENGINEER
PEG Newfoundland and Labrador
SATISH SUD
SIGNATURE
17 - APR - 2012
DATE
NEWFOUNDLAND & LABRADOR

Revision					Remarks
Nº	By	Verif.	Appr.	Date	
01	RA	PA	SS	17-Apr-2012	Re-issued for use
00	RA	PA	SS	16-Mar-2012	Issued for use

TABLE OF CONTENTS

PAGE

List of Tables

List of Figures

1 INTRODUCTION

As part of the Lower Churchill Project, Nalcor is planning to build a bipolar HVdc transmission system to transfer power from Muskrat Falls to Soldiers Pond (Island Link). The scheme would comprise about 388km of overhead line in Labrador, 688km overhead line in Newfoundland and about 30km of undersea/land cable at the Strait of Belle Isle. The scheme is being planned as a bipolar configuration rated at 900 MW, ±350 kV as measured at the Muskrat Falls ac commutating bus [1, 2]. However, the scheme shall be designed for bipolar and monopolar operation.

This report presents a description of HVdc configurations, HVdc control hierarchy, control locations, modes of operation, and operating and control strategies of the scheme, as applicable to the Island Link. This report presents the basic philosophy of these aspects and the final implementation requirements to be developed and presented as part of the Technical Specifications.

2 CONFIGURATIONS

Figure 2.1 shows the different states that an HVdc transmission scheme could operate depending on the design and requirements. This is a general diagramatic representation of available options of an HVdc point-to-point transmission scheme, and depending on the design features and requirements some of the options shown in Figure 2.1 (which will be identified in the following sections), may not be applicable to the Island Link.

A detailed description of each of these states is given in Section 5 and a brief description is presented below.

The Island Link is being designed as a bipolar configuration with ability to operate as a monopolar during outage of a pole. In bipolar configuration it will operate with ground return only. However, in monopolar configuration it can operate either in ground return or metallic return mode.

In addition to its rated voltage and rated power transmission configuration, from Muskrat Falls to Soldiers Pond, the scheme shall also be designed to operate at reduced voltage, reverse power flow, open line test and loop power flow conditions, which are designated as Operational Modes.

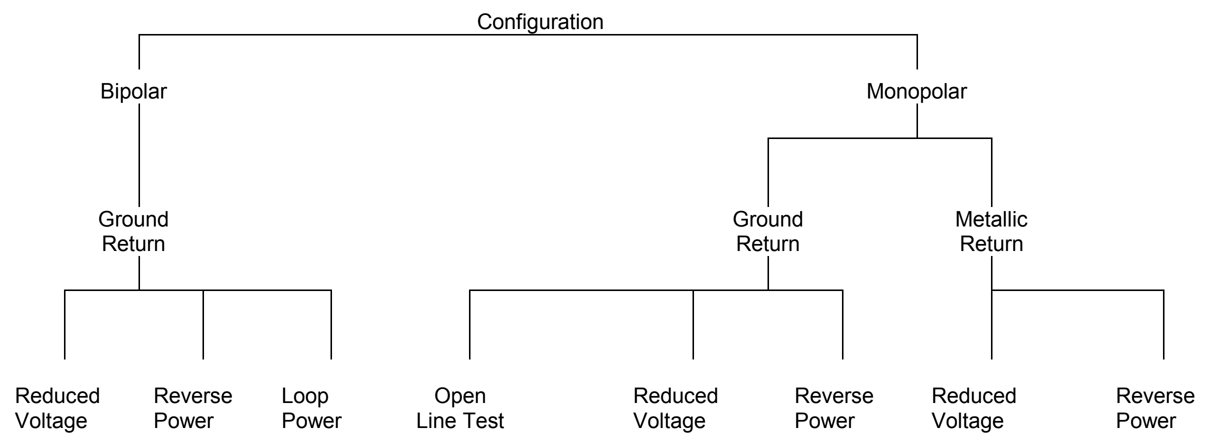
For the purpose of clarity the different levels of operation are defined below:

1) Configuration Modes:
    a) Bipolar Modes (ground return)
    b) Monopolar Modes (ground return or metallic return)
2) Operational Modes:
    a) Reduced Voltage Mode
    b) Reverse Power Mode
    c) Open Loop Test Mode

d) Loop Power Mode

Figure 2-1 also shows the applicable operational modes for each of the configuration modes. For example, loop power flow is not possible in monopolar mode while the rest of the three operational modes are possible in both the configuration modes.

Figure 2-1: Operational Modes



Full Voltage mode and Forward Power mode are the regular modes. Reduced Voltage and Reverse Power are special cases of the regular modes.

Any pole can be operated in power control or current control. These are set points issued by the operator.

3 CONTROL LOCATIONS

The HVdc system shall be designed to operate from any of the four locations: Muskrat Falls Converter Station Control Room, Soldiers Pond Converter Station Control Room, Nalcor Energy Control Centre and Nalcor Energy Backup Control Centre.

In addition to the switching and control of the HVdc system, the switching and control of generators at the Muskrat Falls and synchronous condensers at the Soldiers Pond also shall be coordinated with the HVdc transmission.

The control functions shall be active from only one of the above three locations at any one time. Transfer of control from one location to the other shall be performed locally from the site that has control at the time. The controlling site can request a transfer to one of the other sites or one of the other sites can request a transfer from the controlling site. This will be carried out via telephone and once the arrangements have been agreed upon, the controlling site will hand over control to the new site. The detailed transfer methodology will be developed as part of the specifications.

The required control functions at each location are presented below:

3.1 Muskrat Falls Converter Station Control Room

Full control and monitoring of the HVdc transmission system as well as ac side reactive power/ac voltage, HVdc switchyard and associated 315 kV ac switchyard at Muskrat Falls is required.

3.2 Soldiers Pond Converter Station Control Room

Full control and monitoring of the HVdc transmission system as well as ac side reactive power/ac voltage, HVdc switchyard and associated 230 kV ac switchyard at Soldiers Pond is required.

3.3 Nalcor Energy Control Centre

Full control and monitoring (except open-line testing) of the HVdc transmission system and ac side reactive power/ac voltage (Muskrat Falls and Soldiers Pond), associated 315 kV ac switchyard at Muskrat Falls, associated 230 kV ac switchyard at Soldiers Pond and HVdc switchyard is required.

3.4 Nalcor Backup Energy Control Centre

This acts as a backup to the Main ECC and shall have the same features as the Main ECC.

3.5 Muskrat Falls Generating station

The starting, synchronization, dispatching and stopping of the Muskrat Falls generators shall be performed remotely from ECC/BCC and locally from the Muskrat Falls generating station control room, or at the unit control board.

3.6 Soldiers Pond Synchronous Condensers

The starting, synchronization and stopping of the synchronous condensers at the Soldiers Pond shall be performed remotely from the ECC/BCC. However, starting and stopping the condensers shall be possible from the local controls in the Synchronous Condenser Control room, or at the unit control board.

Close and open operations of the dc switchyard grounding switches shall be performed by local controls in the corresponding switchyard only.

4 CONTROL HIERARCHY

4.1 Master / Slave Selection

This is a bipole hierarchical level controller that permits the operator to select which of the two converter stations will be the master station for the purpose of operational control of the HVdc system. Operator commands such as dc power/current orders, ramp rate settings, starting and stopping of poles, and dc voltage reduction will be allowed to be performed from the master station only.

4.2 Control Hierarchy

Each converter station will be provided with the following four major controllers in the following hierarchical order:

a) Converter firing control

b) Pole current control

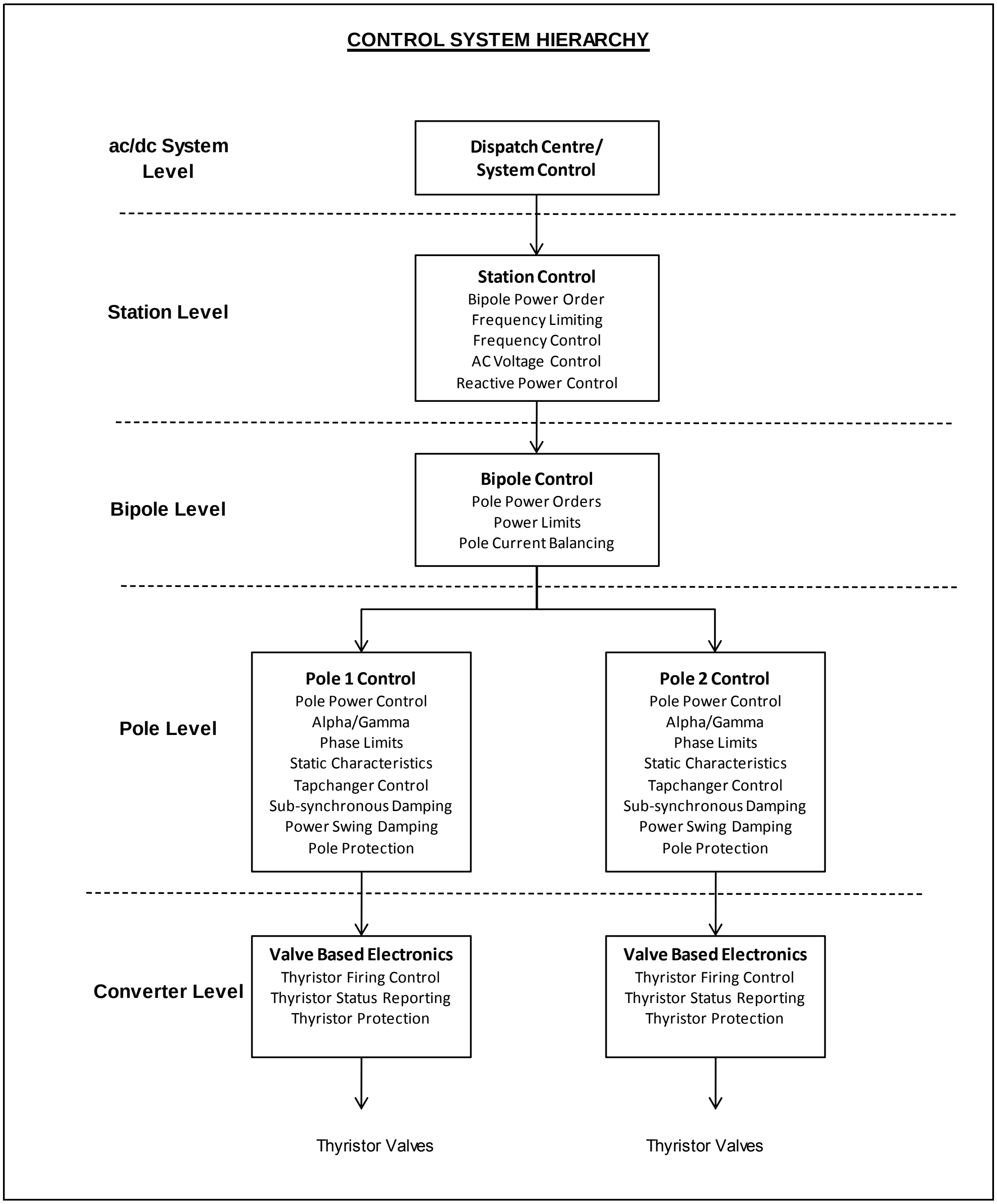
c) Bipole power control

d) Station control

ac/dc System Level control will be carried out exclusively at the Energy Control Centre.

This hierarchy is illustrated in Figure 4-1.

Figure 4-1: Control System Hierarchy



4.2.1 Converter Firing Control

This is the innermost controller among the converter controls, and essentially an open loop control that synchronizes the firing to the commutating ac bus voltages, translates the firing angle (alpha) order into firing pulses and distributes them to the individual valves.

4.2.2 Pole Control

This is a closed loop control system that includes the basic control functions that are required for a stable HVdc system. These basic control functions include the current control, voltage control, extinction angle control, power control and tap changer control. The controller tries to maintain the control variable at the reference value by comparing and adjusting the actual value with the reference value.

Each converter station pole is provided with an independent pole controller that maintain the dc voltage and current within that pole at desired values.

For the operator defined voltage and power order, the pole control calculates the corresponding current order $I_{ord.}$ The closed loop current control system tries to maintain the I_{ord} at the desired value in each pole. The measured pole current is compared with the current order and the amplified output of the error is fed to the converter firing controller to achieve the desired current. The same current controller is applied at both the rectifier and inverter with current margin subtracted from the I_{ord} at the inverter to provide control coordination between the two converters.

4.2.3 Bipole Power Control

The bipole power controller is used for scheduled power orders and calculation of current order for each pole. The set power order is divided by the bipole voltage to get the I_{ord} that is fed to the current controller. The same bipole power controller is implemented at both the converter stations. This can act either to transmit the ordered power or stabilize the system frequency, in either the rectifier or inverter ac systems, within a certain range.

At the loss of one pole this controller increases the power order to the healthy pole within its prescribed limits.

Supplemental signals such as power oscillation damping (modulation signals) and frequency signals are fed into this controller.

4.2.4 Station Controller

This controller is provided at each station to manage shunt bank switching, reactive power exchange, bus voltage, power reduction under low ac voltage, tie line flow control, frequency controller, etc. This is a high level controller.

5 MODES OF OPERATION

5.1 Bipolar Mode

This is the normal mode of operation with current flow in each pole. This could be a balanced or unbalanced operation resulting in equal or unequal currents in each pole. In this mode of operation the total power is limited to 900 MW at the rectifier under maximum ambient temperature.

5.2 Monopolar Mode

The bipolar HVdc system goes to monopolar operation when one of the pole conductors (overhead line or cable), or one of the converters becomes out of service. There are two monopolar operating modes, i.e. monopolar ground return mode and monopolar metallic return mode as described below.

The OLTC tap changers shall be provided with sufficient range to operate in these monopolar operating modes, and at all the short-term, long-term overload and continuous ratings including Reduced Voltage Operation.

There shall be sufficient reactive power available to operate at the short-term overload rating.

5.2.1 Monopolar Ground Return Mode

If one pole of a bipolar system has to be blocked either due to faults or otherwise, the second pole shall be able to operate in monopolar mode automatically without power interruption. The healthy converter pole will be connected to its own overhead line and submarine/underground cable system while the return current will be through the ground path consisting of the electrode lines and the shoreline ponds.

5.2.2 Monopolar Metallic Return Mode

In case of any limitations from the use of ground currents and/or the shoreline pond electrodes, an alternate path through the pole conductors of the blocked pole, termed as “Metallic Return Mode”, is used.

In this mode the pole current flows through the healthy pole and returns through the conductor of the other pole which is out of service. This mode is for emergency or maintenance conditions only, wherein a converter pole or electrode is out of service. Under these conditions there will be higher losses and consequently reduced power transfer.

5.3 Reduced Pole Voltage Operation Mode

A reduced pole dc voltage operation mode shall be provided on each pole of the dc transmission system to allow operation under conditions where the dc line insulators are contaminated and cannot withstand full voltage. This mode can also be invoked as the final re-start attempt following a dc overhead line fault.

The pole dc voltage reference shall be adjustable between 80% and 100% of rated dc voltage. Operation in reduced voltage mode imposes additional duty on the OLTC tap range, reactive power, harmonic filtering, thyristor snubber circuitry, etc. Due to these reasons the amount of current transfer during this mode needs to be evaluated carefully.

This mode invariably results in reduced power transfer if no additional equipment is provided. If power reduction is not allowed it has to be clearly stated in the specifications.

If both poles operate in reduced voltage mode, current could be balanced similar to the full voltage operation. Otherwise, either unbalanced current has to be allowed or current balancing has to be specified.

When reduced voltage operation is initiated or reset by the operator when in operation, the dc voltage shall ramp smoothly to the new dc voltage reference over a suitable time interval determined by the Contractor. It shall be possible to stop the voltage decrease or voltage increase ramp at any time. In such cases, the voltage reference shall be the voltage at which the ramp was stopped.

The tap-changer control shall adjust the converter transformer tap so as to result in the optimum firing angle consistent with the reduced voltage operation.

The pole power capability calculation shall recognize this operating mode and shall make the necessary adjustments to ensure proper operation in this mode, including all current limits.

All modulation signals shall remain active in this mode.

The HVdc controls shall be designed so that the performance requirements stated herein are met.

It shall be possible to order reduced dc pole voltage operation as follows:

- Manually with the pole de-energized
- Manually with the pole energized. A function shall be provided to allow a smooth transition from full voltage to reduced voltage with minimal disturbance to the transmitted dc power by simultaneously adjusting the dc voltage and current to maintain a constant dc power during the transition.
- Manually with the pole energized at dc voltage control terminal when there is no telecommunications available.
- An automatic switchover to reduced voltage mode shall also be initiated by the dc line protection

It shall be possible to order a restoration to full dc voltage as follows:

- Manually when the pole is de-energized

- Manually when the pole is energized. A function shall be provided to allow a smooth transition from reduced dc voltage to rated dc voltage with minimal disturbance to the transmitted dc power by simultaneously adjusting the dc voltage and current to maintain a constant dc power during the transition.
- Manually with the pole energized at the dc voltage controlling terminal when there is no telecommunications available.

5.4 Reverse Power Operation Mode

The dc system control and protection shall be designed to accommodate dc power transfer from Muskrat Falls Converter Station to Soldiers Pond Converter Station normally. It shall also be possible to transfer power from Soldiers Pond to Muskrat Falls. If full power transfer is required it has to be stated in the specifications. With remote chances of reverse power transfer for the Island Link the reverse power feature will be specified but without adding any extra equipment.

Operator controls shall be provided for selection of pole power transfer direction at the operator locations specified herein.

The Contractor shall provide features to change automatically, upon selection of the power transfer direction, any control parameters that require different adjustment in order to achieve the specified performance.

Switching of power transfer direction shall not result in an abrupt voltage reversal on the dc pole. The voltage shall be smoothly brought to zero and then smoothly ramped to the opposite polarity. This should be coordinated with the cable charging properties.

5.5 Open Line Test Mode

This mode of operation is available only at either converter station (local control) and not from the Energy Control Centre. The control system shall be designed to test the voltage withstand capability of the line pole, including adjustable dc voltage application, after maintenance work is completed and prior to restarting dc power transfer over that line pole. It shall be possible for the operator to safely deblock a converter pole into an open circuit with local dc line pole switches closed and remote cable terminal station or converter station dc line pole switches open and adjust the line voltage to any value between zero and 1.05 p.u. to test the local converter station equipment and the line pole connected to it. Open line test mode shall be provided only as a local control function. In this test mode, deblocking of the remote converter station pole shall be inhibited and any open-line type of protections and protections which detect low dc voltage on the converter pole shall be blocked. All necessary protections shall be provided to protect safety of the equipment in the converter stations and cable terminal stations in the test mode. It shall be possible to perform the open line test using the converters of one pole while the other pole is in operation.

This mode of operation is available only at either converter staion (local control) and not from the Energy Control Centre, however, this should be stated in the specifications.

The open line test mode shall have two operating mode options:

a) Manual Mode

In this mode the operator manually starts the pole, adjusts the firing angle in order to control the dc voltage to the desired level then manually reduces the voltage before stopping. The allowable ramp rate shall be adjustable between 1.0 p.u. per minute and 10 p.u. per minute. The control mode shall also limit the maximum time at which the voltage stays at the set voltage adjustable from infinite down to 50 ms.

b) Automatic Mode

In this mode the operator will start the open line test sequence which will automatically deblock the converter pole, ramp the voltage up to a predetermined level (up to 1.05 p.u.) then hold for a pre-set time prior to ramping the voltage down and blocking the converter pole.

During the ramping process the operator shall be able to stop the process. In this case the voltage will remain at the value at which the hold occurred. It shall then be possible to restart the ramp to increase or decrease to voltage as desired. It shall also be possible to block the pole at any time without first ramping to zero.

5.6 Loop Power Flow Mode

The transmission line in certain geographic areas is prone to rime icing and glazed ice conditions, causing heavy ice loading. It is expected that if the dc is lightly loaded the chances of ice accretion are high.

Under light HVdc transmission conditions, close to the rated power shall be circulated in each pole but in opposite directions, thus minimizing the chances of ice accretion on pole conductors. The net power delivered through the dc system would be the dc line losses in addition to the light load power requirements.

The amount of power transferred on each pole shall be adjusted to minimize the ground current.

The control system shall be designed to permit operation of each pole in pole-mode rather than in bipole mode. As an operational mode, this feature shall be configured automatically, without manual intervention, once a command is given to operate in this mode.

In the event of a pole block in this operating mode, the resulting overvoltage will be controlled by the synchronous condensers and, if necessary, switching off of the shunt filter banks.

6 OPERATING STRATEGIES

The Muskrat Falls to Soldiers Pond HVdc project shall be designed to have the following basic operating strategies in both directions of power transfer:

a) Bipole Power Control Mode

b) Pole Individual Power Control

c) Current Control with Telecom

d) Current Control without Telecom

A brief description of each of these control modes is given below:

6.1 Bipole Power Control Mode

This will be the primary control mode for the dc system. In this control mode, the closed-loop control system shall control the dc power referenced at the rectifier station to the scheduled power order provided by the operator at the active operator control location. This control mode shall be available in each of the operating modes given above in Section 5, except in open line test mode and loop power mode.

If both poles are selected to bipole power control, then the bipole power allocator function shall assign equal current orders to each pole so as to minimise the ground current in the electrode. If both poles are operating at the same voltage then the power transfer in each pole will be equal. However, if one pole is operating at reduced voltage while the other is at full voltage then the power transferred in each pole will be in the ratio of the pole voltages.

If one of the poles is selected to one of the individual control modes (pole individual power control or current control with telecom) or if one pole is in current control without telecom, then the power in that pole may be fixed at a desired level and the net bipole power transfer shall be maintained at the ordered level by the pole which is in bipole power control. In this case the ground currents will in general not be balanced and the power order of the pole in bipole power control will be the difference between the bipole power order and the actual power transfer of the pole which is in the individual control mode.

The bipole power control mode shall have two options for operational control:

a) Manual Control

The desired bipole power order and power ramp rate will be entered from the selected operator control location (local or remote) of the converter station selected to be the master station for operator control.

On activation of the execute power order the dc power transfer level on the bipole shall be linearly changed at a rate adjustable to values between 10 MW per minute and 100 MW per minute to the desired bipole power order. A display shall be provided which shall show that a ramp is in progress and the ramp rate. A bipole ramp stop function shall also be provided which when activated shall cause the ramp to end and the power order to remain at the value reached when the ramp stop function was executed. If the ramp is re-started it should be able to be re-started at a different ramp rate from the intial selection.

b) Automatic Control

In this option the bipole power order shall be controlled automatically in response to either automatic control or a pre-programmed power transfer curve which will define the power transfer over the daily, weekly or monthly load cycle.

The operator shall be able to switch freely from manual to any of the automatic control options above and vice-versa. When switching between manual and any of the automatic control options above there shall be no disturbance to the transmitted power. The power shall ramp smoothly between the actual power at the time of switchover and the power order of the mode being enabled at the power ramp rate defined in the manual control option.

When both poles are in bipole power control, the power controls shall ensure that equal currents will normally flow in each dc line pole conductor and that ground current is minimized. High ground currents would be tolerated only in the case of monopolar ground return operation and when, due to equipment limitations or other reasons, it is not possible to achieve balanced line pole currents. Equal pole current shall be maintained to the extent possible even when one converter pole is operating at reduced voltage.

If the power order to either pole exceeds the continuous capability of the equipment in that pole because of outages of equipment in that pole or other reason such as reduced voltage operation, then the excess portion of the power order shall be allocated to the other pole up to the continuous capability of the pole including overloads and vice-versa.

If there is a reduction in the capability of one pole of the dc system which would result in a decrease in the actual dc power transfer, the power controls shall quickly and automatically restore the power transfer to a level as near as possible to ordered level by increasing the current in the other pole up to the inherent capability and short time overload rating of the equipment.

The power controls shall generate an alarm to the system operator when the current or power flow in the pole is beyond the continuous capability of the equipment and shall automatically reduce the power to a safe level after the specified inherent and short time overload has been utilized.

Redistribution of power orders between poles due to loss of capability is only required on the pole which is in bipole power control. If one pole is in individual control and the other pole is in bipole power control the pole which is in bipole power control is required to compensate for loss of capability in the pole which is in individual control. The pole, which is in individual control, is not required to compensate for loss of capability in the pole which is in bipole power control.

If the scheduled bipole power order is altered by signals required for overall system performance enhancement, the control system shall control the dc bipole power to the net resulting power order.

All signals which modulate the power order and therefore contribute to the effective power order shall be individually monitored, along with the effective bipole power order, on the station transient fault recorder, or equivalent device. The Contractor shall provide output signals suitably buffered for this purpose for all such signals originating in equipment in his supply.

Should the Contractor's design include functions which automatically switch from constant power control mode to another mode such as constant current control during transients, or for cases when a power controller failure is detected, the dc current shall remain within ± 1% of the values prior to mode switching to current control. Reverting to power control could be initiated manually or automatically according to a pre-selection command from the operator. Reverting to power control shall be smooth, with the same limits applicable. An alarm shall be produced when the constant power control mode is automatically switched to another mode.

During conditions such as transients when the current control with telecom mode is in effect, modulation signals shall not be disabled.

The design of the bipole dc power control and pole individual power control shall be such that the calculated pole current order will not be affected by the instantaneous change of dc voltage which will occur during transients.

It shall be possible to select one or both of the poles to operate in an individual mode. It shall be possible to start/stop or to set the pole power/current reference of poles which are in individual control independently.

When one of the poles is in current control with telecom mode or current control without telecom mode or pole individual power control mode, the power controls shall ensure that the ordered bipole power given from the operator controls is still transmitted up to the capability of the remaining pole which is operating in bipole power control.

6.2 Pole Individual Power Control

This control mode shall be provided separately for each pole.

In this control mode the power transfer of the pole is maintained at the pole power order set-point. In this mode the pole power transfer is not influenced by the bipole power order.

The pole individual power control shall have the following features:

- It shall be possible to increase or decrease the pole power transfer by specifying a new pole power order and pole power ramp rate then activating the execute power order. The power shall then ramp smoothly to the new pole power order at the pole power ramp rate.
- Only manual control of the power order is required. It is not required to provide an automatic function as for the bipole power control.
- All modulation controls and limiters shall remain active in this control mode.

6.3 Current Control with Telecom

This mode shall be provided for each pole.

In this control mode the dc controls maintain the pole dc current order at the set point value. Coordination of the current orders between the terminals is maintained automatically through the normal current order coordination functions, via the HVdc telecontrol system.

This control mode shall have the following features:

- It shall be possible to change the current order by specifying a new order then initiating a ramp similar to the power control or alternatively to increment or decrement the current order in adjustable steps. The step size adjustment and step increment/decrement shall be operator selected from a control point on the SCADA.

- All modulation controls and limiters shall remain active when operating in this mode.

6.4 Current Control without Telecom

An emergency pole current control mode of operation shall be provided on each pole to permit operation of that pole when HVdc telecontrol equipment or the communication channels required for coordination of current orders are not available. This mode of operation shall be initiated automatically on loss of telecommunications. If both poles are in bipole power control mode then current mode without telecom shall not be automatically initiated unless there is a loss of communications to both poles.

An alarm signal shall be issued if there is a switchover to current control without telecom mode. During the telecommunications outage the pole power orders shall track the dc actual power transmitted. The control system shall automatically resume bipole power control when the telecommunications are restored. During switchover to current control without telecom and back to pole individual power control, there shall be no change in measured dc power and dc current.

When one pole is in current control without telecom it shall be designed to not degrade the performance of the other pole.

7 CONTROL STRATEGIES

The converter controls will normally maintain the power flow over the bipole at the value ordered by the operator. The rectifier controls will normally control the transmitted pole current and the inverter controls will regulate pole voltage to maintain sending end voltage. Under disturbed conditions, additional fast-acting control systems will be required to ensure stable post-disturbance recovery of the Island and Labrador ac systems. In the stability studies carried out as part of this project, the application of fast-acting, frequency controllers were considered for the Island Link at Soldiers Pond (inverter) and for the Maritime Link at Bottom Brook (rectifier) [3].

7.1 Control Strategies Required Following ac System Faults

The stability studies demonstrated that, in order to avoid load shedding on the island following a major disturbance, it will be necessary to implement the following control strategy:

- In the event of a rapid reduction in the Island frequency the dc power level on the Island Link should be increased, and
- The dc power level on the Maritime Link should be reduced.

The studies also demonstrated the following specific requirements:

- In the event of a permanent 3-phase fault at Muskrat Falls on one of the lines to Churchill Falls, when three or fewer units are operating at Muskrat Falls, at peak load and with full import from Labrador, the dc power order on the Island Link must be reduced prior to the re-start of the dc link. The pre-fault power order must be reduced by an amount equivalent to the export being delivered to Nova Scotia over the Maritime Link.

- In the event of a 3-phase fault at Bay d'Espoir 230 kV or any other 230 kV bus to the west of Bay d'Espoir, or in the event of a temporary bipole fault on the Island Link, or in the event of a 3-phase fault at Muskrat Falls on one of the 315 kV lines to Churchill Falls, the power being exported on the Maritime Link must be reduced to zero. This will automatically occur for the faults at Bay d'Espoir and to the west as the voltage at Bottom Brook will fall to a level where the Maritime link will block. For other faults, the reduction can be effected by means of a frequency controller at the Bottom Brook converter. The requirement to reduce the export over the Maritime Link for a fault at Muskrat Falls only applies for peak load conditions when three or fewer units are operating at Muskrat Falls.

The controls should automatically adjust the ordered power flow, so that if a power reduction occurs in either pole below the ordered value due to the sudden loss of pole capability, then the power level in the healthy pole will be adjusted by increasing power, within the capability of the converter, as determined in the Basis of Design as follows:

- 200% capability for 10 minutes
- 150% capability continuously

This should take place even when one of the poles is manually blocked when the system is in bipolar mode of operation. Conversely when the second pole is brought in manually into bipolar mode, the controls should automatically ramp up the power in the incoming pole while ramping down the power on the other pole until balanced bipolar mode of operation is achieved. The ability to change the power order should also be reflected in the current order controls so that during and following a fault, the HVdc link can be switched from power order control to current control.

7.2 Control Strategies Following a Pole Fault

For a fault occurring on one pole of the Island link, the control strategy to be followed will depend upon the location of the fault. In all cases, the converters will be adjusted to reduce the dc current in the faulted pole to zero in the conventional way. Since the majority of overhead line faults are transient in nature, it is normal practice to re-start the converters on the faulted pole after allowing a suitable de-ionization time for the transient fault to extinguish completely. Since the Island Link will include a submarine cable section across the Straits of Belle Isle, it will be necessary to discriminate between overhead line faults and submarine cable faults. In the case of a fault on one submarine cable, the conventional re-start of the converters following the reduction of the pole current to zero should be inhibited since almost all cable faults are permanent faults and re-energization is not recommended. In the case of an overhead line fault, a maximum of four re-starts should be permitted before shutting the pole down permanently until the fault can be located and repaired.

7.3 Control Strategies Following a Converter Block

For a temporary bipole fault on the Island link, a reduction in the dc power order on the Island link, following fault clearance, would allow for a longer de-ionization period to be considered for the fault. Without any reduction in power order, the maximum time permitted until re-start after a bipole fault is 12-cycles/200 ms and the frequency controller must be disabled for a period of 500 ms following the fault. With a power order reduction, the restart time can be extended to 300-340 ms. A reduction in power order will also be required for a 6-cycle/3-phase fault at Muskrat Falls 315 kV that results in the outage of one of the 315 kV lines to Churchill Falls, when only three or fewer units are operating at Muskrat Falls. This reduction in power order is not required when all four units are operating at Muskrat Falls and only applies during the peak load period. The reduction required in the power order is equivalent to the export that was provided over the Maritime Link prior to the fault.

The controls should ensure that, upon an HVdc telecontrol or telecommunications system(s) failure causing loss of further HVdc telecontrol signal updating, the power transmission is maintained at the last ordered value prior to failure.

Even during a telecommunications failure, it should be possible to change power both in response to manual power order changes and to power modulation signals without any risk for loss of current margin.

Throughout the year and at all load levels, certain outages on the Island network (230 kV line outages and generator outages) will result in steady-state line overloads following the fault. In order to avoid these overloads, a reduction is required in the export over the Maritime Link and, in some cases, a reduction of the import over the Island Link. A summary of the reductions in steady-state power that must be implemented to avoid overloading of the existing and planned 230 kV lines on the Island is shown in Table 7-1.

7.4 Islanded Operation

The HVdc scheme could result in an islanded mode of operation at the rectifier for the loss of both 315 kV lines connected to the Churchill Falls system. In such a case, the HVdc system shall be able to operate under frequency droop characteristics, and also damp out low frequency system oscillations due to governor interaction.

Table 7-1: Summary of Mitigating Measures

Scenario	Load Level	Outage	Mitigating Measure
BC-1	Winter Peak	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 158MW to 96MW
BC-2	Winter Peak	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 239MW to 96MW
BC-3	Winter Peak	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 158MW to 10MW
BC-5	Spring/Fall Peak	230kV Soldiers Pond and Western Avalon#1 (TL217W)	Maritime Link reduction-From 158MW to 98MW
			Island Link reduction-From 814MW to 774MW
		Largest Generator at Upper Salmon	Maritime Link reduction-From 158MW to 124MW
BC-6	Spring/Fall Peak	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 158MW to Zero
BC-7	Spring/Fall Peak	Any 230kV line between Soldiers Pond and Bottom Brook	Maritime Link reduction-From 500MW to 350MW
			Island Link reduction-From 814MW to 664MW
BC-8	Summer Day	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 158MW to 90MW
BC-9	Summer Day	All outages	No reductions required
BC-10	Summer Day	Any 230kV line between Soldiers Pond and Bottom Brook	Maritime Link reduction-From 500MW to 100MW
			Island Link reduction-From 814MW to 414MW
BC-11	Summer Night	Largest Generator at Upper Salmon	Island Link increase-From 81MW to 108MW
BC-12	Summer Night	230kV Bottom Brook and Buchans (TL233)	Maritime Link reduction-From 320MW to 240MW
BC-13	Summer Night	Any 230kV line between Soldiers Pond and Bottom Brook	Maritime Link reduction-From 320MW to 240MW
			Island Link reduction-From 435MW to 355MW
		Largest Generator at Bay d'Espoir	Maritime Link reduction-From 320MW to 240MW
BC-14	Winter Peak	Largest Generator at Bay d'Espoir	Maritime Link or Island Link import-Increase by 135MW
BC-15	Spring/Fall Peak	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 158MW to 76MW
BC-16	Summer Day	Any 230kV line between Soldiers Pond and Bottom Brook	Maritime Link reduction-From 500MW to 250MW
			Island Link reduction-From 594MW to 344MW
BC-17	Summer Night	Largest Generator at Bay d'Espoir	Island Link increase-From 200MW to 220MW
BC-18	Winter Peak	Largest Generator at Bay d'Espoir	Maritime Link reduction-From 158MW to 96MW
BC-19	Spring/Fall Peak	Any 230kV line between Soldiers Pond and Bottom Brook	Maritime Link reduction-From 500MW to 350MW
			Island Link reduction-From 814MW to 664MW

8 REFERENCES

[1] Nalcor, “Lower Churchill Project – Basis of Design”, LCP-PT-ED-0000-EN-RP-0001-01

[2] Nalcor, “Design Philosophy for LCP Converters”, LCP-PT-ED-0000-EN-PH-0019-01

[3] SLI Report, “Lower Churchill Project-Stability Studies“, SLI Report No. 505573-480A-47ER-004, Nalcor Report No.ILK-SN-CD-8000-EL-RP-0001-01

.