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THE Lower Churchill PROJECT

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DC1020 - HVdc System Integration Study

Volume 3 - Comparison of Conventional and CCC HVdc Technology

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Executive Summary

Preliminary transient stability analysis of the Lower Churchill multi-terminal HVdc project has been completed in order to compare the performance of conventional HVdc technology with the performance of capacitor-commutated converter (CCC) HVdc technology. The analysis has been performed on the year 2016 Island system peak load (1600 MW) case with 800 MW bipolar infeed (base case BC1-DC1). The purpose of the HVdc technology comparison is to provide a recommendation and justification for the direction of the remainder of the transient stability studies, i.e. whether conventional or CCC HVdc technology should be pursued.

Sensitivity to the new refinery load (175 MW) planned to be installed at Pipers Hole was included in the analysis. In addition an evaluation of the benefits of adding series compensation to the 230 kV lines between Bay d'Espoir and Pipers Hole was performed.

One 300 MVAR high inertia synchronous condenser (identical to those used by Manitoba Hydro) is required to be in-service at all times at both the 230 kV Pipers Hole bus and at the 230 kV Soldiers Pond bus. Without these synchronous condensers the dynamic performance of the system is unstable or unacceptable for various disturbances.

The following conclusions can be made:

1. Conventional HVdc Technology

With the refinery load in- or out-of-service, the system becomes unstable for a three-phase-to-ground fault at Bay d'Espoir on one of the Pipers Hole 230 kV lines. This is due to the fact that the Bay d'Espoir generators are faulted and simultaneously the HVdc experiences a commutation failure which results in a momentary loss of the 800 MW DC infeed. Cross-tripping the refinery load if it is in service does not mitigate the instability.

With the refinery load in-service a three-phase-to-ground fault at Pipers Hole on a Bay d'Espoir line would require the 175 MW new refinery load to be cross-tripped in order to maintain system stability.

With the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole, recovery from a three-phase-to-ground fault at Bay d'Espoir on one of the Pipers Hole 230 kV lines is possible if the 175 MW new refinery load is cross-tripped. However voltage criteria is violated at the Bay d'Espoir and Sunnyside buses during recovery. In addition, with series compensation, a fault at Pipers Hole on a Bay d'Espoir line no longer requires the 175 MW new refinery load to be cross-tripped.

2. CCC HVdc Technology

The main benefit of CCC HVdc technology in this system is the ability of the HVdc to avoid commutation failure for a three-phase-to-ground fault at Bay d'Espoir. By avoiding the commutation failure for a Bay d'Espoir fault, the severity of this fault on the overall system is greatly reduced. This is true for both the operating scenarios with and without the new 175 MW refinery load in-service.

With CCC HVdc technology a three-phase-to-ground fault a Pipers Hole on a Bay d'Espoir line would require the 175 MW new refinery load to cross-tripped. The load cross-tripping can be avoided if 50% series compensation is installed on both 230 kV lines between Bay d'Espoir and Pipers Hole.

3. Other Load/Generation Dispatches

It should be noted that the base power flow case studied (1600 MW load, 800 MW bipolar infeed, BC1-DC1) in this preliminary transient stability analysis is not necessarily the most stressed case. The 600 MW monopolar infeed case as well as the future peak 1800 MW Island load case are expected to provide slightly worse results as less Island spinning reserve is available. It is likely that, in these cases, series compensation on the Bay d'Espoir-Pipers Hole lines will be a necessary AC system solution to improve dynamic performance and increase robustness especially for disturbances that are already on the verge of violating dynamic performance criteria. However, this is not yet known for certain at this point in time. Even if the system is considered not stressed to its maximum extent, the need and benefit of series compensation is quite evident.

A summary of findings for the potential solutions to maintain system stability are given below:

1. The use of conventional HVdc technology with the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole is technically feasible if cross-tripping of the 175 MW new refinery load for specific contingencies is acceptable.
2. The use of CCC HVdc technology without the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole is technically feasible if cross-tripping of the 175 MW new refinery load for specific contingencies is acceptable.
3. The use of CCC HVdc technology with the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole is also technically feasible and it avoids cross-tripping of the 175 MW new refinery load.

It was noted from the study results that system stability can be maintained with the conventional HVdc with the application of the series compensation on the 230 kV lines between Bay d'Espoir and Pipers Hole if crosstrip of the 175 MW new refinery load is permitted. The CCC HVdc technology does provide some added benefit in that the 175 MW refinery load does not require cross-tripping if series compensation on the 230 kV lines between Bay d'Espoir and Pipers Hole are installed. This benefit, however, is fairly limited. On the other hand, there is some uncertainty associated with the application of the CCC to a long distance multi-terminal HVdc link.

Based on the results of this study the following recommendations are made:

1. Install 50% series compensation on the 230 kV lines between Bay d'Espoir and Pipers Hole to improve dynamic performance of the system.
2. The conventional HVdc technology with the above mentioned series compensation is recommended. The dynamic performance of the system with the conventional HVdc is acceptable with the exception of voltage criteria violations under certain disturbances. These violations are considered as attributed to system inherent problems and can be dealt with separately.

There is a marginal benefit of the application of CCC HVdc technology, but due to uncertainties with its application this technology is not recommended.

1. Introduction

This report compares the dynamic performance of NFL system with conventional HVdc technology to that with CCC HVdc technology in the Lower Churchill multi-terminal HVdc link. This report discusses the results of preliminary transient stability analysis for the WTO DC1020, the DC system integration studies for the Lower Churchill Project (LCP). New Island system facilities, existing Island system upgrades and potential special protection systems such as cross-tripping of loads are identified as required for both technologies to maintain system stability and provide acceptable system voltage recovery following normal-clearing three-phase faults and slow-clearing single line-to-ground faults.

Although there is currently a back-to-back CCC HVdc system in operation, CCC technology has not yet been applied to a long distance HVdc transmission system. The application of a CCC to the Lower Churchill Project has the potential of improving performance due to the basic nature of CCC, however it also adds another degree of complexity to the interconnected ac/dc system and should be used only if it is demonstrated that there is a substantial performance benefit.

The transient stability analysis was performed using the PSCAD version 4.2.1 software package.

All analysis for this comparison has been performed on the year 2016 Island system peak load (1600 MW) case with 800 MW bipolar infeed at Soldiers Pond (case BC1-DC1).

1.1 Objectives

The objectives of the preliminary transient stability analysis are to determine:

1. Island system upgrades required to maintain acceptable dynamic system performance of the AC and DC systems for conventional HVdc technology.
2. Island system upgrades required to maintain acceptable dynamic system performance of the AC and DC systems for CCC HVdc technology.
3. Comparison of CCC and conventional HVdc technology performances in the Island AC system.
4. Develop recommendations on the required system reinforcement and the use of HVdc technology and request for guidance from NLH as to the direction of the remainder of the WTO DC1020 transient stability analysis.

1.2 Procedure

The transient stability analysis was carried out using the following procedure:

1. Create a PSCAD model of the NLH system based on power flow analysis case BC1-DC1. Setup the model for both the conventional and CCC multi-terminal HVdc technologies.
2. Perform transient stability studies by applying normal-clearing (100 ms) three-phase faults and slow-clearing (250 ms) single line to ground faults at the expected worst-case locations in the NLH Island

system to ensure that the transient stability criteria, including rotor angle stability and transient under-voltage criteria is met.

3. When transient stability criteria is not met, determine acceptable mitigation including cross-tripping of the 175 MW new refinery load and the application of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole
4. Compare the dynamic performance results and impact of load cross-tripping and series compensation for the conventional HVdc technology and the CCC HVdc technology.
5. Provide recommendations and discussion on conventional HVdc technology versus CCC HVdc technology.

2. Background

Discussions were held between NLH and TGS on November 12 and 13 in Winnipeg regarding preliminary findings of the transient stability studies prior to the work performed for this report. Personnel involved in the meetings included Paul Humphries and Peter Thomas of NLH, and Peter Kuffel, Rebecca Brandt and Dan Kell of TGS. A summary of the discussions is provided below.

A summary of the initial findings presented by TGS is given below:

- Initial findings showed that for the 1600 MW load base-case, with the HVdc operating in bipolar mode with 800 MW infeed, performance of the interconnected ac/dc system was worse than expected when compared to results of earlier studies performed by Teshmont. A summary of the initial findings is given below:
    - Various faults within the island ac network result in unacceptable voltage depressions and even voltage collapse. These are most pronounced in the Bay d'Espoir and Sunnyside regions of the network.
    - Results were worse for faults which cause a large disruption of the generators at Bay d'Espoir and simultaneous commutation failure of the HVdc infeed.
    - The addition of more and larger rating synchronous condensers within the Island system provided some improvement, however the overall improvement was marginal.
    - Fast recovery of the HVdc power infeed following fault removal provides some benefit. The rate at which the HVdc power recovers must be balanced off against the risk of a secondary commutation failure if it is too fast.
    - The addition of a third 230 kV ac circuit between Bay d'Espoir and the Sunnyside region provides substantial improvement to the overall system recovery.
    - Cases with the HVdc operating monopolar with 600 MW infeed appear to be worse that the 800 MW bipolar configuration.
- The degraded performance when compared to results from the earlier Teshmont study were attributed to the following:
    - Impact of long cable on commutation performance and HVdc recovery at Soldiers Pond following faults.
    - The system load used in the two studies is considerably different; in particular the current study includes a 175 MW refinery load at Pipers Hole.
    - In the current study the loads are modeled as constant current for the real portion and constant impedance for the reactive portion, whereas in the earlier Teshmont study both the real and reactive portion of loads were modeled as constant impedance loads. The use of constant current for real power loads provides more realistic results and is much more onerous on the transient performance of the network.

  - Results of the earlier Teshmont study indicate that the system was unstable for a fault on the Bay d'Espoir to Sunnyside line. Mitigation of this was not provided in the study.
  - Load shedding was used in the earlier Teshmont study whereas in the present study one of the main goals is to avoid load shedding.
- Based on the initial findings a number of optional configurations were considered as discussed below:
  - Additional synchronous condensers were provided in order to improve overall performance. Results showed that this was only marginally effective.
  - The location of the five 50 MVA combustion turbines was varied to determine its effect on overall system performance. The location was seen to have little impact.
  - A two terminal Gull Island to Soldiers Pond HVdc link was investigated in order to determine the impact of the long cable section from Cape Ray to Salisbury on the performance of the Soldiers Pond converter. As expected, removal of the long cable section resulted in improved commutation performance and the ability to recover the HVdc infeed faster. Overall system performance was improved; however, a fault on the Bay d'Espoir to Sunnyside ac line still resulted in voltage collapse.
  - A damping function was developed and added to the multi-terminal HVdc controls in order to allow faster recovery from commutation failures. The addition of the new damping function provided recovery from commutation failures at Soldiers Pond for the multi-terminal HVdc which were comparable to that obtained for the two-terminal HVdc.
  - A two-terminal Capacitor Commutated Converter (CCC) HVdc link was examined. As expected the CCC provided improved commutation performance and provided some immunity to commutation failures. In particular, a fault at Bay d'Espoir no longer resulted in a commutation failure; hence, the overall system performance for this fault was very good and the voltage collapse avoided.

A discussion of general study requirements followed and is summarized below:

- Synchronous condensers which are added to support the HVdc infeed should be added at the Soldiers Pond and Pipers Hole buses due to space constraints at the Sunnyside station.
- Initial synchronous condenser parameters will be based on the machines used by Manitoba Hydro which have a heavier inertia which will improve overall system performance.
- The five 50 MVA combustion turbines should initially be located at the 230 kV bus to which the new refinery load is connected. A sensitivity to locating these at Holyrood should be undertaken.
- The need for a third 230 kV circuit should be avoided if at all possible.
- Transient post contingency voltages should remain above 70% for all buses.
- Steady state post contingency voltages must remain above 90% at all buses except Come-by-Chance where it must be above 93%.

- It is acceptable to trip the new refinery load (or portion of it) in order to avoid voltage collapse for faults between Bay d'Espoir and Pipers Hole. This should be avoided if possible.
- There is a need to identify system performance issues with and without the new refinery load in service in order to better understand ac system upgrades which are required to support the HVdc infeed and those required to support the new refinery load.

A discussion of how to proceed with the study followed and is summarized below:

- Since performance of the multi-terminal HVdc with the damping function included in the controls was nearing that of the two terminal HVdc (Gull Island to Soldiers Pond only) it was decided that a two terminal option should not be considered at this time.
- Since the preliminary look at CCC provided some immunity from commutation failures, a three terminal CCC model should be developed and used to better evaluate the potential performance benefits.
- A more comprehensive comparison of the performance of CCC versus conventional HVdc should be conducted at this stage of the study. This comparison will form the basis for recommending which configuration should be used in the transient stability studies.
- Continued work on the transient stability studies should wait until a recommendation has been put forward regarding the HVdc configuration and approval has been received from NLH.
- In order to better identify ac system upgrades which are associated with the new refinery load cases which consider the refinery load out of service need to be studied. Under this configuration, the Bay d'Espoir units should be re-dispatched such that one is running is synchronous condenser mode and the five 50 MVA combustion turbines should be located at Holyrood.
- Both 800 MW bipolar and 600 MW monopolar HVdc operating configurations should be considered. The 1600 MW base case load should be used for the 800 MW bipolar case, and a modified case with the refinery load out of service and the Bay d'Espoir units re-dispatched should be used for the 600 MW monopolar configuration.

3. Conventional and CCC HVdc Technology

The basic building block of the HVDC line commutated converter (LCC) is the six pulse Graetz bridge as shown in Figure 1 which is connected in series to result in a 12-pulse bridge as shown in Figure 2.

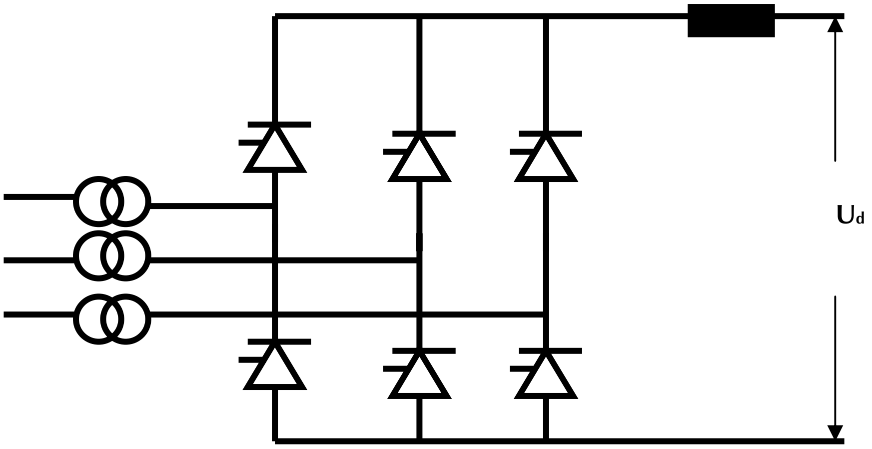


Figure 1 - Six Pulse Graetz Bridge

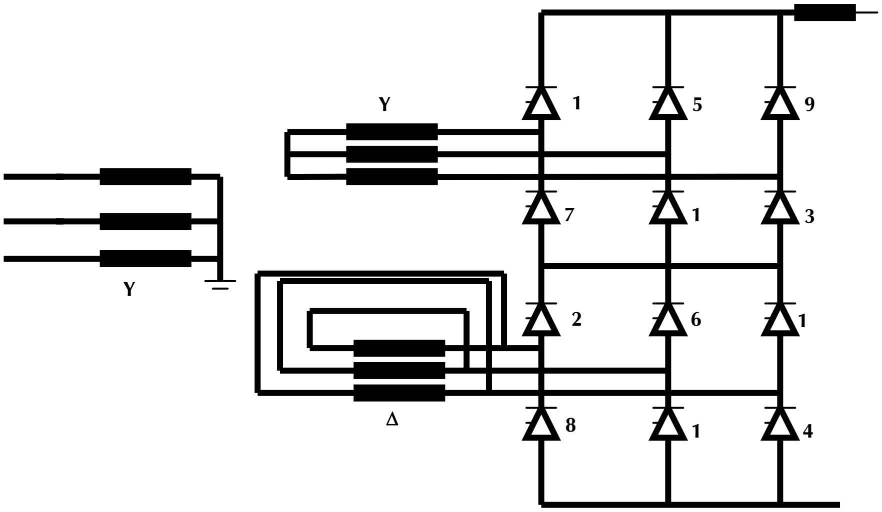


Figure 2 - Twelve Pulse Converter Bridge

Although this configuration offers efficient, reliable and economical operation, it has a number of notable drawbacks as follows:

1. The converter relies on the line voltage for the commutation process, therefore at the inverter the valve must be triggered sufficiently early of the line voltage zero crossing to provide it with enough commutation margin. Because of this dependence, the converter is susceptible to commutation failures in the event of ac system voltage depressions and when operated in weak ac systems.
2. The conventional arrangement presents a special problem with long HVDC cables since any reduction of the inverter bus voltage causes a corresponding decrease in dc voltage and thus an increase in dc current because of the cable capacitance discharge. The sudden increase in dc current in turn causes the extinction angle gamma to decrease, which increases the probability of commutation failures.
3. The demand for reactive power, which is typically about 0.5 pu of the rated active power must be supplied by shunt reactive power elements at the converter or from the ac system itself.
4. Upon sudden load rejection due to a block of the converter, an ac overvoltage occurs due to the loss of power and the fact that the capacitive shunt compensation elements (ac filters) remain connected to the ac busbar. Usually these shunt banks are removed from service to protect the equipment and to reduce the overvoltage.

The capacitive commutated converter as shown in figures 3 can mitigate these drawbacks.

In principle the addition of the series capacitors results in an additional commutating voltage. As a result of this additional commutating voltage, an increased firing angle range is obtained for both rectifier and inverter operation. This increased commutation voltage also results in a reduction of the overlap angle (commutation interval), leading to lower reactive power consumption.

Because of the presence of the capacitors, the commutation circuit includes both inductance and capacitance; therefore the basic equations of the conventional converter are no longer valid. The capacitors are charged with a polarity that aids in the commutation process. The size of the capacitors can be selected so that, in theory, the firing angle (alpha) can be increased well beyond 90 degrees. The commutation voltage also now has a phase lag and a higher amplitude when compared to the real bus voltage. This results in an additional commutation margin provided by the capacitors, consequently a smaller extinction angle is possible.

The capacitors also provide an additional commutation margin proportional to the dc current. For example, as the dc current increases, the voltage on the capacitors increases, resulting in an increase of the extinction angle. This is contrary to the situation in a conventional converter where the extinction angle decreases with increasing dc current. This certainly improves the commutation failure performance. This characteristic is very beneficial for an HVDC system with a long cable. It also has better performance in the event of remote ac system faults.

One major advantage of a capacitive commutated converter as compared to a conventional inverter is that for minimum commutation margin control it has a positive impedance while the conventional inverter has a negative impedance. This positive impedance characteristic will improve the inverter performance in long dc cable transmission. Figure 3 shows the basic configuration of a Capacitor Commutated Converter (CCC).

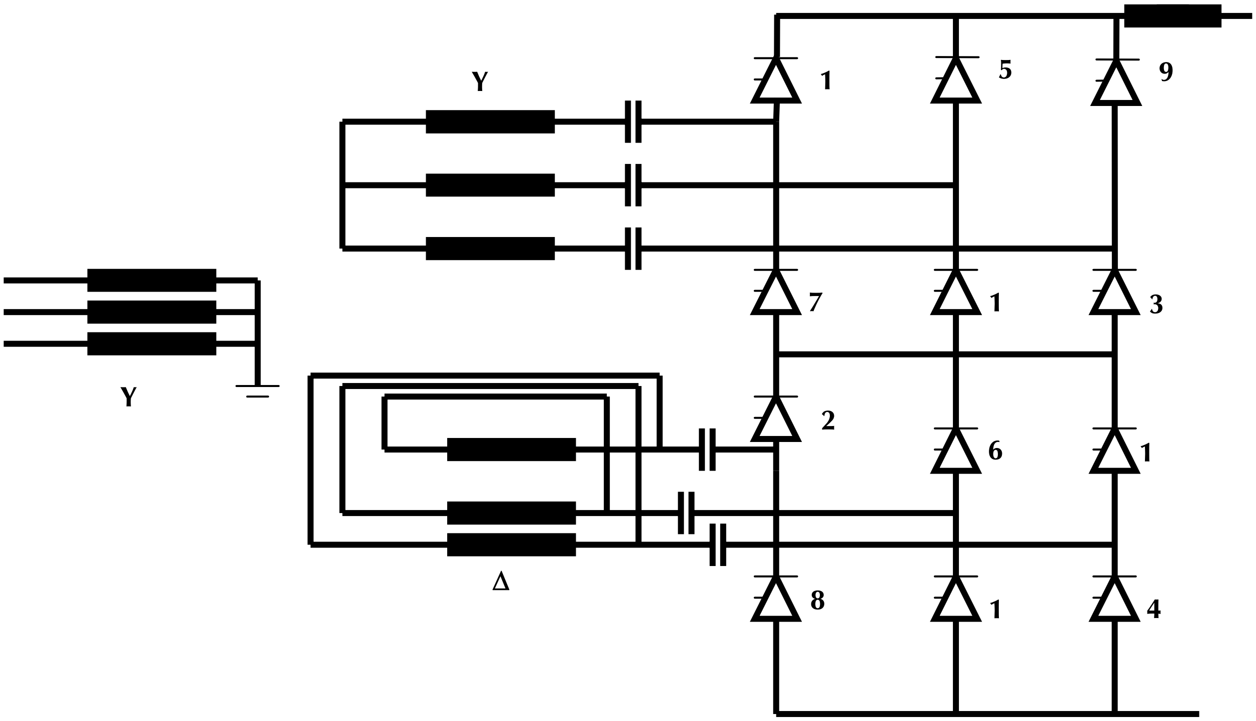


Figure 3 - CCC Converter Bridge

In this circuit the capacitors are connected between the converter and the ac bus on the valve side of the converter transformer. Because of the presence of the capacitors on the valve side, the CCC typically has a higher voltage impressed on the valves as compared to the conventional HVDC converter. This results in higher requirements for the snubber circuits and an increased voltage rating for the arrestor compared to the conventional HVDC, therefore it requires an increase in the valve insulation. The increased voltage stress is in the range of 10%. On the other hand, the short circuit current upon valve short circuit at the rectifier is lower than the conventional HVDC valve. This is due to the fast charging of the capacitors which produces a counter voltage that will limit the peak value. The typical protection during the valve short circuit fault is to block the valves with no bypass action. However it is standard in the design to assume that the blocking may fail and three or four loops of fault current will continue depending on the speed of the circuit breaker trip. The capacitor counter voltage will certainly reduce the peak of these loops. The capacitor counter voltage will also reduce the blocking voltage seen by the valve involved in the short circuit.

The phase currents of the CCC are very similar to the phase currents of a conventional HVDC. The only difference is that the currents during the overlap interval are not only part of the sine wave with fundamental frequency but also contain a component with the natural frequency of the capacitor/inductor circuit. As explained earlier, because the capacitor voltage supports the commutation of current from one valve to another, the overlap angle is reduced. The reduction will lead to a slight increase in the ac harmonics. The increase is in the range of 1% to 2%.

In a CCC the rating of the converter transformer is reduced because the reactive power flowing through the transformer is reduced. Obviously the no load losses of the converter transformer are lower due to the reduced rating of the unit. However, the load losses are increased due to the increased harmonic currents and the increased commutation jumps.

Since the CCC is self regulating in terms of reactive power consumption, the number and size of the ac filters can be reduced. Therefore, upon sudden block of the converter the resulting overvoltage on the ac bus is minimized.

Although there is currently a back-to-back CCC HVdc system in operation, CCC technology has not yet been applied to a long distance HVdc transmission system. Two specific areas of concern with the application of CCC to a long distance HVdc transmission system is the increased potential for system resonances and control system instabilities due to ac/dc system interactions. It can be assumed that the major suppliers would be able to overcome these issues; however the impact cannot be fully understood without extensive design studies. Therefore there is some uncertainty associated with the application of the CCC and its recommendation should only be justified when clear and substantial performance benefits are possible.

4. Study Models for Transient Stability Analysis

The preliminary transient stability analysis was performed using the year 2016 Island system peak load (1600 MW) case with 800 MW bipolar infeed into Soldiers Pond, corresponding to power flow case BC1-DC1 from the WTO DC1020 power flow analysis.

The real power portion of all loads are represented as constant current loads and the reactive power portion of all loads are represented as constant impedance loads.

4.1 AC System Representations

4.1.1 NLH Island System

Due to the length of computation time required to perform simulations in electromagnetic transients software, a reduced NLH Island AC system model is used to represent the AC system and its initial power flow conditions in PSCAD.

Based on the results of the previous preliminary stability analysis, it is known that more dynamic reactive power support as well as increased inertia will be required in the Island system. Preliminary analysis suggests that one 300 MVAR synchronous condenser be in-service at all times at both the Pipers Hole 230 kV bus and at Soldiers Pond 230 kV bus.

The year 2016 and future peak Island power flow cases have several significant modifications when compared to the existing system today:

1. A new large refinery load (175 MW, 85 MVAr) is planned to be in-service near Piper's Hole, between Bay D'Espoir and Sunnyside. As well, a nickel smelter load (83 MW, 40 MVAr) is planned for the Long Harbour area. The internal NLH studies for the additions of these loads have not yet been completed, therefore it is expected that system impacts due the loads will be observed in this HVdc feasibility study.

2. NLH is planning to convert units #1 to #3 at Holyrood to synchronous condensers as part of the Lower Churchill Project to meet ESCR requirements. In addition NLH is planning to install five 50 MW combustion turbines (CT) at Holyrood to meet load requirements between 2010 and the HVdc 2015 in-service date. These CTs will be specified with the capability to operate in synchronous condenser mode. The Holyrood station will have a total of eight (8) synchronous condensers available for voltage control and in support of ESCR with the following ratings:

   a. Unit #1 – 142/-72 MVAr
   b. Unit #2 – 142/-72 MVAr
   c. Unit #3 – 150/-69 MVAr
   d. CT Units #1-5: 63.5 MVA at 0.85 power factor leading

In addition, a 54 MW CT at Hardwoods is capable of operation as a synchronous condenser with a +28/-25 MVAr rating.

4.1.2 Labrador System

As described in the WTO DC1020 power flow analysis report, the Labrador system is represented by a weak system configuration. This weak configuration is achieved by removing the Muskrat Falls generating station, a 230 kV line from Gull Island to Muskrat Falls and a 735 kV line from Churchill Falls to Gull Island Generating Station.

The Labrador terminal of the HVdc system is operating as the rectifier, supplying rated power to Newfoundland Island and to New Brunswick.

In all test cases considered, the HVdc frequency control at Soldiers Pond is disabled as this function has not yet been optimized. The implementation of the frequency controller should provide improved post-contingency frequency response.

4.1.3 New Brunswick System

The New Brunswick system was represented by an equivalent voltage source with a system strength of [redacted] MVA.

4.2 Multi-terminal HVdc Link Representation

The Gull Island terminal was operated in a bipolar configuration as the rectifier, supplying rated power to the Island and New Brunswick terminals both operating as inverters.

Two different HVdc technologies were modeled, one representing conventional HVdc, the other representing CCC HVdc.

4.3 Sensitivities

The following sensitivities were studied:

1. Impact of new refinery load in- or out-of-service. The new refinery load (175 MW, 85 MVAR) at Pipers Hole is in-service in the base power flow case BC1-DC1. Sensitivity to this load being out-of-service is studied as power flow studies indicated this load has significant impact on the Island system during contingencies particularly between Bay d'Espoir and Soldiers Pond.

2. Impact of CCC HVdc technology and conventional HVdc technology.

3. Cursory impact of adding series capacitors to the 230 kV lines between Bay d'Espoir and Pipers Hole.

4.4 Assumptions

The following assumptions were made for each case:

1. All large synchronous condensers (units 1-3) at Holyrood are in-service.
2. If the new refinery load at Pipers Hole is in-service then the five new CTs currently planned for installation as synchronous condensers at Holyrood are relocated to Pipers Hole. If the new refinery load at Pipers Hole is out-of-service then the five new CTs are left as synchronous condensers at Holyrood. In all cases, one of these five CTs is assumed to be out-of-service for maintenance.
3. In the case testing sensitivity to new refinery load out-of-service, the generation at Bay d'Espoir is re-dispatched to maintain approximately 60 MW on each of units 1-6 with unit7 operating as a synchronous condenser.
4. One 300 MVAR synchronous condenser (high inertia of 2.2) is in-service at both Pipers Hole 230 kV bus and Soldiers Pond 230 kV bus in all cases.

4.5 Contingencies

Results of the power flow analysis provide indication as to which fault cases are expected to cause worst-case dynamic performances. Table 1 lists the contingencies that were studied in this preliminary transient stability analysis.

Table 1
Contingencies for Preliminary Transient Stability Analysis

Contingency	Description
1	100ms 3PF at Bay d'Espoir, clear Bay d'Espoir to Pipers Hole 230 kV line
2	100ms 3PF at mid-point, clear Bay d'Espoir to Pipers Hole 230 kV line
3	100ms 3PF at Pipers Hole, clear Bay d'Espoir to Pipers Hole 230 kV line
4	100ms 3PF at Sunnyside, clear Sunnyside to Western Avalon 230 kV line
5	100ms 3PF at Soldiers Pond, clear Soldiers Pond to Western Avalon 230 kV line
6	250ms LGF at Soldiers Pond, clear Soldiers Pond to Western Avalon 230 kV line

It is important to note that most of the line faults are of single-phase-to-ground type. Whereas, the second contingency in the above Table-1 represents a tower failure the probability of which is very remote as compared with the single-phase-to-ground faults. As noted from the study results, this contingency results in violation of the set voltage criteria. It is expected that a single-phase-to-ground fault will not result in voltage violation.

5. Transient Stability Analysis

The purpose of this preliminary transient stability analysis is to compare conventional and CCC HVdc technology and to determine the required Island AC system upgrade to dynamically support the 800 MW DC infeed at Soldiers Pond. These AC system upgrades are determined for both conventional HVdc technology and CCC HVdc technology in order that a recommendation can be made to steer the direction for the remainder of the transient stability analysis.

5.1 Study Procedure

Results of the steady state AC contingency analysis from the DC1020 load flow report were used to identify the expected worst-case contingencies. These contingencies, as described in Table 1, are applied and the simulations run for 5 seconds.

Bus voltages, system frequency, generator speeds and various transmission line power flows in the NLH system are monitored along with various HVdc parameters. The purpose is to identify any contingencies that result in a violation of system stability criteria or that result in poor HVdc dynamic performance. If a problem is discovered, mitigation in the following forms is studied:

1. HVdc control parameter optimization.
2. Trip of the 175 MW new refinery load at Pipers Hole.
3. 50% series compensation on both 230 kV lines between Bay d’Espoir and Pipers Hole.

5.2 Dynamic Performance Criteria

The following dynamic performance criteria are used to determine the Island AC transmission solution:

1. Transient undervoltages following fault clearing should not drop below 0.7 pu.
2. The system should be stable and reasonably well damped following fault clearing.
3. Under-frequency load shedding should be avoided if at all possible.

5.3 Study Results

The major NLH Island load centre is located east of Bay d’Espoir on the Avalon Peninsula, while the majority of the generation is located west of Bay d’Espoir. This can result in heavy west to east power flow on the 230 kV transmission system, in particular between Bay d’Espoir, Sunnyside, Western Avalon and Soldiers Pond. In addition, approximately 255 MW of new industrial load (refinery and smelter) is planned to be installed along this heavily loaded west to east corridor, which increases the loading on these 230 kV lines. As a general result this can cause voltage and rotor angle stability issues for the Island system along with steady state voltage depression and thermal overloading on lines in this corridor.

The HVdc infeed into Soldiers Pond generally has a positive steady state impact on the Island transmission system as it off-loads this west to east power flow by injecting power closer to the load centre. Faults within the Island ac network that cause a commutation failure at Soldiers Pond will however result in a transient loss of the entire HVdc infeed (800 MW in this case) during the commutation failure and for a short period following AC fault clearing as the HVdc power is recovering (approximately 200-300ms depending on the fault). In particular, faults causing commutation failure while simultaneously disturbing the Bay d'Espoir generators to a high enough degree (i.e. a fault very near Bay d'Espoir) can be enough to result in system instability with the existing Island AC system.

Many of the issues are not necessarily due solely to the HVdc infeed but are also due to the lack of transmission linking the generation in the west of the Island to the load in the east of the Island, and also due to the large new refinery loads that are planned to be installed in the area. Issues as presented are also due simply to the fact that the HVdc infeed represents approximately half of the Island's total generation in this case while the Island has very little spinning reserve. Transient loss of this infeed at the same time as disturbing the Bay d'Espoir generators results in a huge disturbance to the system and an immediate momentarily large energy mismatch.

It was quickly discovered that in order to survive faults between Bay d'Espoir and Soldiers Pond, more reactive power support than first identified in the power flow analysis would be necessary. Power flow analysis indicated the need for 200 MVAR at Sunnyside and one 150 MVAR synchronous condenser at Soldiers Pond. Initial stability analysis indicates that one 300 MVAR high inertia synchronous condenser is required to be in-service at both Pipers Hole 230 kV bus and Soldiers Pond 230 kV bus at all times. This indicates the need for two 300 MVAR synchronous condensers to be installed at both Pipers Hole and Soldiers Pond to account for maintenance outages.

The discussion of the worst-case transient stability results is split into two major sections – the first section discusses dynamic performance results with the new refinery load at Pipers Hole in-service; the second section discusses worst-case dynamic performance results with the new refinery load out-of-service. Within each of these sections the performance of conventional HVdc technology is compared with CCC HVdc technology. In addition, a brief discussion regarding the benefits of adding 50% series compensation to the 230 kV lines between Bay d'Espoir and Pipers Hole is included for the worst-case faults.

Among all cases, the worst-case disturbance in terms of maintaining system stability and 0.7 pu transient under-voltage criteria was found to be a three-phase fault on one of the Bay d'Espoir to Pipers Hole lines.

Also in all cases, a slow-clearing single line-to-ground fault at Soldiers Pond causes a commutation failure for the length of the fault, however the DC is able to recover and the AC system dynamic performance criteria is met. Minimum frequency dips to 0.978 pu on the second swing, but this is expected to be improved with frequency controller tuning on the HVdc.

A three-phase fault at Soldiers Pond on a Soldiers Pond-Western Avalon line and a three-phase fault at Sunnyside on the Sunnyside-Western Avalon line both cause commutation failure but the fault recoveries are within acceptable dynamic performance criteria.

The mitigation option looking at 50% series compensation on the Bay d'Espoir to Pipers Hole lines changes the original power flow case by lowering the impedance of the lines and drawing more power through them. The system intact case with 50% series compensation has 194 MVA flow on each Bay d'Espoir-Pipers Hole line and during an outage of one of the two parallel lines the line flow is increased to 368 MVA for the case being studied (BC1-DC1). Appendix A contains single line diagrams showing the Island system power flow for both the system intact and Bay d'Espoir – Pipers Hole line out scenarios.

For a complete summary of results please refer to Appendix B. For a set of plots showing dynamic performance results please refer to Appendix C-F.

5.3.1 New Refinery Load In-Service

With the new refinery load at Pipers Hole in-service, the five new CTs (synchronous condensers) that are planned to be installed at Holyrood are re-located to Pipers Hole.

5.3.1.1 Conventional HVdc Technology

The worst-case disturbance is a three-phase fault at Bay d'Espoir on one of the 230 kV lines to Pipers Hole. This fault causes the HVdc to fail commutation which collapses the HVdc power momentarily. At the same time it also causes a large disturbance of the Bay d'Espoir generators. The system cannot survive this disturbance and becomes unstable.

Tripping the 175 MW new refinery load at Pipers Hole during the fault was tested to see if system stability could be maintained, but dropping this load is not enough.

A fault at Pipers Hole on one of the Bay d'Espoir lines also causes system instability but can be mitigated by cross-tripping the 175 MW new refinery load.

With the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole recovery from a fault at Bay d'Espoir on one of the Pipers Hole 230 kV lines is possible with tripping of the 175 MW new refinery load. It should be noted that although the system was stable and did recover, some voltage criteria violations were observed at the Bay d'Espoir and Sunnyside buses. Furthermore, with the addition of the series compensation, recovery from a fault at Pipers Hole on one of the Bay d'Espoir lines no longer requires cross-trip of the refinery load.

In summary, the use of conventional HVdc technology (without any system reinforcement) results in system collapse for a fault at Bay d'Espoir. However, addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole in combination with crosstripping of the 175 MW new refinery load (when necessary) provides suitable mitigation for all contingencies.

A complete set of results is contained in Appendix C.

5.3.1.2 *CCC HVdc Technology*

With CCC technology the previously worst-case Bay d'Espoir fault now does not cause the HVdc to fail commutation. By avoiding commutation failure the system response to the fault is well within the accepted dynamic performance criteria. Faults on the Bay d'Espoir to Pipers Hole line were tested at the midpoint of the line and also at Pipers Hole. The midpoint fault location also did not cause a commutation failure and had acceptable dynamic performance.

For CCC HVdc technology the worst-case disturbance is a fault at Pipers Hole on one of the Bay d'Espoir to Pipers Hole lines. This disturbance causes the HVdc to fail commutation and again causes system instability. This fault however, because it is further from the Bay d'Espoir generators, is not as severe as the Bay d'Espoir location for the conventional HVdc technology, and in this case cross-tripping the new 175 MW refinery load is sufficient to maintain system stability and meet dynamic performance criteria.

The results obtained indicate the development of neutral stable oscillations in the dc current approximately 500 ms following recovery from the fault. The oscillations appear to be due to an ac/dc system interaction which results in a imbalance across the capacitors located between the converter transformers and valve groups in the CCC. Due to time limitations, significant effort was not spent on determining suitable mitigation for these oscillations during this study. It is important to note that such oscillations are a real phenomenon and will need to be addressed if the CCC technology is pursued.

With the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole cross-tripping of the 175 MW new refinery load is no longer required for the fault at Pipers Hole on one of the Bay d'Espoir to Pipers Hole lines.

In summary, the use of CCC HVdc technology in combination with cross-tripping of the 175 MW new refinery load (when necessary) provides stable response for all contingencies considered. The addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole eliminates the need to cross-trip the 175 MW new refinery load for all contingencies.

A complete set of results is contained in Appendix D.

5.3.2 *New Refinery Load Out-of-Service*

If the planned refinery load at Pipers Hole does not go ahead, the five new CTs (synchronous condensers) that are planned to be installed at Holyrood are left at Holyrood and not relocated to Pipers Hole. Bay d'Espoir generation is redispatched to operate unit 7 as a synchronous condenser and maintain approximately 60 MW on each of units 1-6.

The cases without the refinery load are far less stressed and generally see improved overall dynamic performance.

5.3.2.1 *Conventional HVdc Technology*

The worst-case disturbance is still a three-phase fault at Bay d'Espoir on one of the 230 kV lines to Pipers Hole. This fault causes the HVdc to fail commutation which collapses the HVdc power momentarily. At the same time it also causes a large disturbance of the Bay d'Espoir generators. The system cannot survive this disturbance and becomes unstable.

With the addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole recovery from a fault at Bay d'Espoir on one of the Pipers Hole 230 kV lines is possible.

In summary, the use of conventional HVdc technology without any system reinforcement results in system collapse for a fault at Bay d'Espoir. The addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole provides suitable mitigation for all contingencies considered.

A complete set of results is contained in Appendix E.

5.3.2.2 CCC HVdc Technology

Similar to Section 6.3.1, the CCC technology provides the HVdc with better immunity to commutation failure and avoids commutation failure for faults midway down the Bay d'Espoir- Pipers Hole line to Bay d'Espoir. Faults at Pipers Hole still cause the HVdc to fail commutation however the dynamic performance of the fault recovery in this case is within acceptable criteria.

With the addition of 50% series compensation on both 230kV lines between Bay d'Espoir and Pipers Hole system recovery was improved.

In summary, the use of CCC technology provides stable response for all contingencies considered. The addition of 50% series compensation on both 230 kV lines between Bay d'Espoir and Pipers Hole resulted in improved recovery for all contingencies considered.

A complete set of results is contained in Appendix F.

5.3.3 Summary of Results – Conventional HVdc versus CCC HVdc

The complete results are summarized in the table below.

HVDC Configuration	Fault Location	Refinery Status	Refinery Crosstrip	Series Compensation	Stable?	Voltage Violations?
Conventional	BDE	IN	0 MW	No	NO	-
	Midpoint	IN	0 MW	No	NO	-
	PH	IN	0 MW	No	NO	-
	BDE	IN	175 MW	No	NO	-
	Midpoint	IN	175 MW	No	YES	none
	PH	IN	175 MW	No	YES	none
CCC	BDE	IN	0 MW	No	YES	none
	Midpoint	IN	0 MW	No	YES	none
	PH	IN	0 MW	No	NO	-
	PH	IN	175 MW	No	YES	none
Conventional	BDE	OUT	-	No	NO	-
	Midpoint	OUT	-	No	YES	none
	PH	OUT	-	No	YES	none
CCC	BDE	OUT	-	No	YES	none
	Midpoint	OUT	-	No	YES	none
	PH	OUT	-	No	YES	none
Conventional	BDE	IN	0 MW	Yes	NO	-
	Midpoint	IN	0 MW	Yes	NO	-
	PH	IN	0 MW	Yes	YES	none
	Midpoint	IN	175 MW	Yes	YES	BDE-0.65 pu, SSD-0.64 pu
	BDE	IN	175 MW	Yes	YES	BDE-0.60 pu, SSD-0.67 pu
CCC	BDE	IN	0 MW	Yes	YES	none
	Midpoint	IN	0 MW	Yes	YES	none
	PH	IN	0 MW	Yes	YES	none
Conventional	BDE	OUT	-	Yes	YES	none
	Midpoint	OUT	-	Yes	YES	none
	PH	OUT	-	Yes	YES	none
CCC	BDE	OUT	-	Yes	YES	none
	Midpoint	OUT	-	Yes	YES	none
	PH	OUT	-	Yes	YES	none

The following salient points are noted from the table above:

- Application of conventional HVdc technology results in system collapse for a number of contingencies with and without the 175 MW new refinery load in service. Also, cross-tripping the new refinery load, if it were in-service, does not avoid system collapse.
- Application of conventional HVdc technology in conjunction with the addition of 50% series compensation to both of the 230 kV Bay d'Espoir - Pipers Hole lines will result in stable recovery from all contingencies considered. For cases with the 175 MW new refinery load in-service, cross-trip of the new load is required for certain contingencies to maintain system stability.

- Application of CCC HVdc technology results in system recovery for all contingencies with and without the 175 MW new refinery load in service. For cases with the 175 MW new refinery load in-service, cross-trip of the new load is required for certain contingencies to maintain system stability.
- Application of CCC HVdc technology in conjunction with the addition of 50% series compensation to both of the 230 kV Bay d'Espoir - Pipers Hole lines will result in stable recovery from all contingencies considered. For cases with the 175 MW new refinery load in-service, cross-trip of the new load is not required for any of the contingencies considered to maintain system stability.

The main benefit of CCC HVdc technology in this system is the ability to avoid commutation failure for a three-phase fault at Bay d'Espoir. By avoiding the commutation failure for a Bay d'Espoir fault, the need for a third 230 kV circuit between Bay d'Espoir and Pipers Hole is eliminated. This fact is true for both the system with and without the new 175 MW refinery load in-service.

In order to maintain system stability, conventional HVdc technology would require the addition of 50% series compensation to both of the 230 kV Bay d'Espoir - Pipers Hole lines and cross-trip of the 175 MW new refinery load at Pipers Hole (for certain contingencies) in order to maintain system stability for all contingencies considered.

It should be noted that the base power flow case being studied (1600 MW load, 800 MW bipolar infeed, BC1-DC1) in this preliminary transient stability analysis is not necessarily the most stressed case. The 600 MW monopolar infeed case as well as the future peak 1800 MW Island load cases are expected to provide slightly worse results as less spinning reserve is available. It is likely that the need for series compensation will be even more apparent in these cases in order to provide an interconnected ac/dc system solution with improved dynamic performance and increased robustness.

6. Conclusions and Recommendations

The following conclusions can be made as a result of the preliminary transient stability analysis:

1. Conventional HVdc Technology

With the refinery load in- or out-of-service, the system becomes unstable for a fault at Bay d'Espoir on one of the Pipers Hole 230 kV lines. This is due to the fact that the Bay d'Espoir generators are faulted and simultaneously the HVdc experiences a commutation failure which results in a momentary loss of the 800 MW DC infeed. Cross-tripping the refinery load if it is in service does not mitigate the instability.

With the refinery load in-service a fault at Pipers Hole on a Bay d'Espoir line would require the 175 MW new refinery load to be cross-tripped in order to maintain system stability.

With the addition of 50% series compensation on both 230kV lines between Bay d'Espoir and Pipers Hole, recovery from a fault at Bay d'Espoir on one of the Pipers Hole 230 kV lines is possible if the 175 MW new refinery load is cross-tripped, however voltage criteria is violated at the Bay d'Espoir and Sunnyside buses during recovery. In addition, with series compensation, a fault at Pipers Hole on a Bay d'Espoir line no longer requires the 175 MW new refinery load to be cross-tripped in order to maintain system stability.

2. CCC HVdc Technology

The main benefit of CCC HVdc technology in this system is the ability of the HVdc to avoid commutation failure for a three-phase fault at Bay d'Espoir. By avoiding the commutation failure for a Bay d'Espoir fault, the severity of this fault on the overall system is greatly reduced. This fact is true for both the system with and without the new 175 MW refinery load in-service.

With CCC HVdc technology a fault a Pipers Hole on a Bay d'Espoir line would require the 175 MW new refinery load to cross-tripped. The load cross-tripping can be avoided if 50% series compensation is installed on both 230 kV lines between Bay d'Espoir and Pipers Hole.

3. Other Power Flow Cases

It should be noted that the base power flow case being studied (1600 MW load, 800 MW bipolar infeed, BC1-DC1) in this preliminary transient stability analysis is not necessarily the most stressed case. The 600 MW monopolar infeed case as well as the future peak 1800 MW Island load cases are expected to provide slightly worse results as less spinning reserve is available. It is likely that the series compensation will either be necessary in these cases or at the least may offer an AC system solution with improved dynamic performance and increased robustness.

The results of this study show that with the application of the series compensation on the 230 kV lines between Bay d'Espoir and Pipers Hole system stability is maintained for all contingencies considered with conventional HVdc technology if crosstrip of the 175 MW new refinery load is permitted. Although the application of CCC HVdc technology does provide some added benefit in that the 175 MW refinery load does not require crosstripping, this benefit is fairly limited, whereas there is some uncertainty associated with the application of the CCC to a long distance multi-terminal HVdc link.

Based on the results of this study the following recommendations are made:

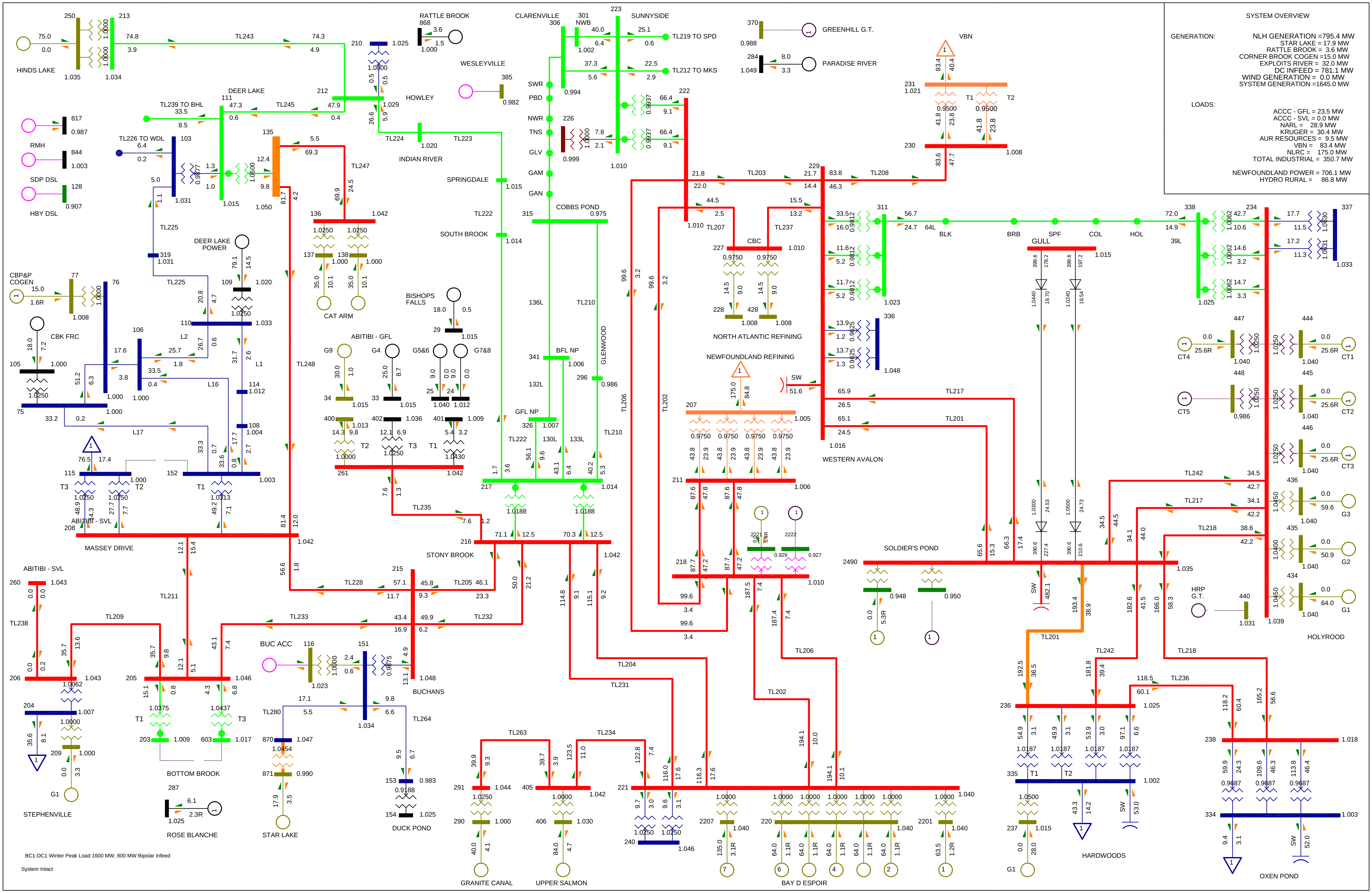
1. Install 50% series compensation on the 230 kV lines between Bay d'Espoir and Pipers Hole to improve dynamic performance of the system.

2. The conventional HVdc technology with the above mentioned series compensation is recommended. The dynamic performance of the system with the conventional HVdc is acceptable with the exception of voltage criteria violations under certain disturbances. These violations are considered as attributed to system inherent problems and can be dealt with separately.

3. There is a marginal benefit of the application of CCC HVdc technology, but due to uncertainties with its application this technology is not recommended.

Appendix A

Island Single Line Diagrams of Power Flows with 50% Series Compensation

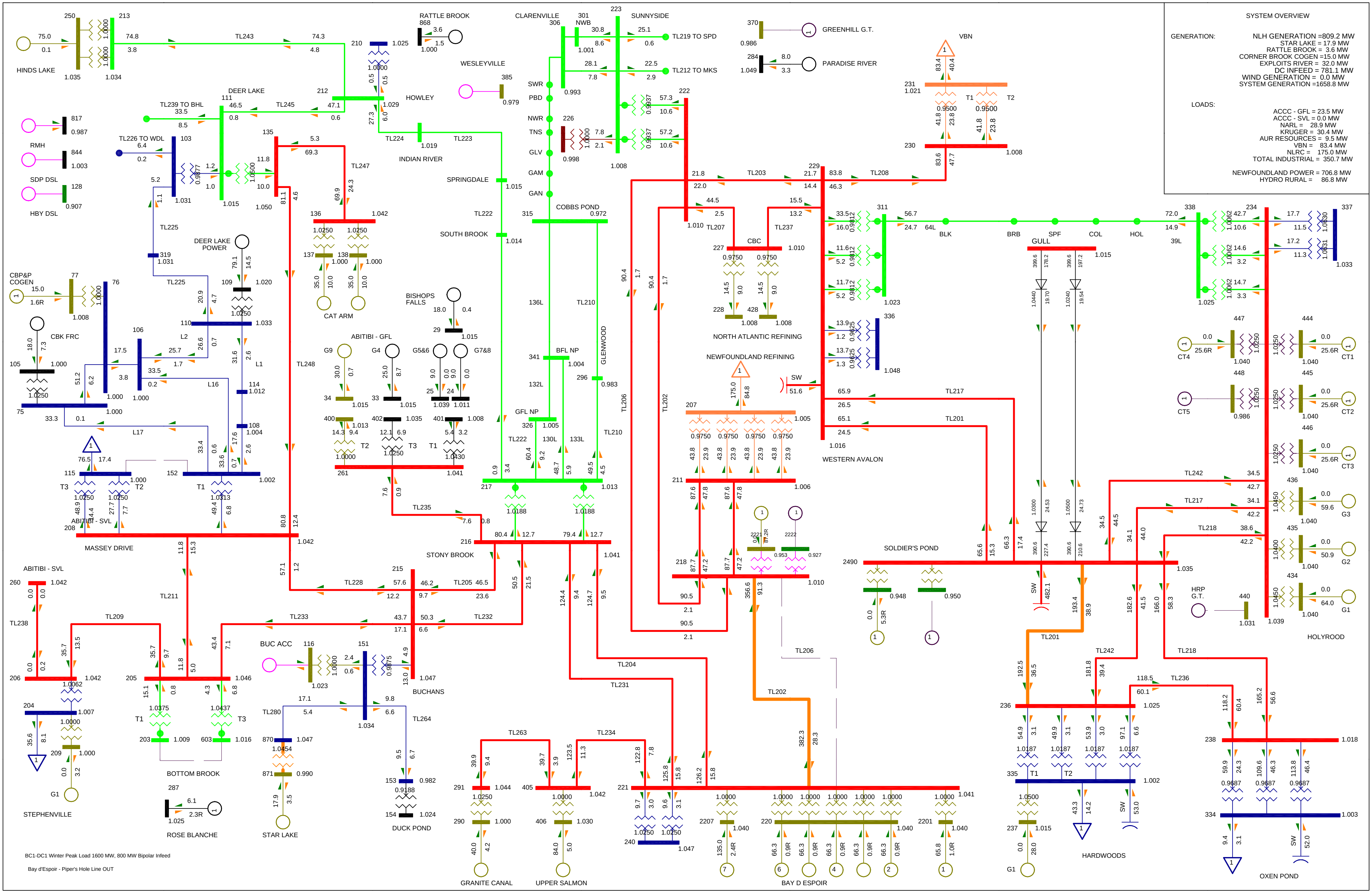


SYSTEM OVERVIEW

GENERATION:
NLH GENERATION =795.4 MW
STAR LAKE = 17.9 MW
RATTLE BROOK = 3.6 MW
CORNER BROOK COGEN =15.0 MW
EXPLOITS RIVER = 32.0 MW
DC INFEED = 781.1 MW
WIND GENERATION = 0.0 MW
SYSTEM GENERATION =1645.0 MW

LOADS:
ACCC - GFL = 23.5 MW
ACCC - SVL = 0.0 MW
NARL = 28.9 MW
KRUGER = 30.4 MW
AUR RESOURCES = 9.5 MW
VBN = 83.4 MW
NLRC = 175.0 MW
TOTAL INDUSTRIAL = 350.7 MW

NEWFOUNDLAND POWER = 706.1 MW
HYDRO RURAL = 86.8 MW



SYSTEM OVERVIEW

GENERATION:
NLH GENERATION =809.2 MW
STAR LAKE = 17.9 MW
RATTLE BROOK = 3.6 MW
CORNER BROOK COGEN =15.0 MW
EXPLOITS RIVER = 32.0 MW
DC INFEED = 781.1 MW
WIND GENERATION = 0.0 MW
SYSTEM GENERATION =1658.8 MW

LOADS:
ACCC - GFL = 23.5 MW
ACCC - SVL = 0.0 MW
NARL = 28.9 MW
KRUGER = 30.4 MW
AUR RESOURCES = 9.5 MW
VBN = 83.4 MW
NLRC = 175.0 MW
TOTAL INDUSTRIAL = 350.7 MW

NEWFOUNDLAND POWER = 706.8 MW
HYDRO RURAL = 86.8 MW

BC1-DC1 Winter Peak Load 1600 MW, 800 MW Bipolar Infeed

Bay d'Espoir - Piper's Hole Line OUT

Appendix B

Summary of Dynamic Performance Results

Case		Synchronous Condensers						Min Transient Voltage After Fault clears (pu)			Min Frequency Deviation (pu)	Comm Fail ?	Stable ?	Notes
		Sunnyside SYNCS	SP SYNCHS	Holyrood SYNCHS	Holyrood CT-SYNCHS	Fault	Load Tripped	Sunnyside	Soldiers Pond	Bay d'Espoir				
REFINERY LOAD IN - No Series Compensation on Bay d'Espoir Piper's Hole Lines - CONVENTIONAL DC														
NC1	1	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (BDE)		🟥	🟥	🟥	🟥	🟥	NO	see case NC1.1a
	2	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (mid)		🟥	🟥	🟥	🟥	🟥	NO	see case NC1.2a
	3	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (PH)		🟥	🟥	🟥	🟥	🟥	NO	see case NC1.3a
	4	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SSD-WAV		0.75	0.90	0.82	0.983	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SP-WAV		0.86	0.94	0.87	0.978	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	BF LGF SP-WAV		0.70	0.92	0.70	0.973	YES	YES	
	1a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (BDE)	175 MW refinery	🟥	🟥	🟥	🟥	🟥	NO	
	2a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (mid)	175 MW refinery	0.81	0.90	0.74	0.987	YES	YES	
	3a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (PH)	175 MW refinery	0.80	0.91	0.79	0.989	YES	YES	
REFINERY LOAD IN - Series Compensation on Bay d'Espoir Piper's Hole Lines - CONVENTIONAL DC														
SC1	1	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (BDE)		🟥	🟥	🟥	🟥	🟥	NO	see case SC1.1a
	2	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (mid)		🟥	🟥	🟥	🟥	🟥	NO	see case SC1.2a
	3	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (PH)		0.75	0.90	0.82	0.983	YES	YES	
	4	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SSD-WAV		0.81	0.90	0.89	0.983	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SP-WAV		0.93	0.95	0.98	0.979	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	BF LGF SP-WAV		0.92	0.97	0.94	0.974	YES	YES	
	1a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (BDE)	175 MW refinery	0.67	0.87	0.60	0.986	YES	YES	
	2a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (mid)	175 MW refinery	0.64	0.86	0.65	0.981	YES	YES	
	3a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (PH)	175 MW refinery	0.82	0.92	0.90	0.990	YES	YES	
REFINERY LOAD IN - No Series Compensation on Bay d'Espoir Piper's Hole Lines - CCC														
NC2	1	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (BDE)		0.969	1.006	0.992	N/A	NO	YES	
	2	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF PH-BDE (mid)		0.97	1.01	1.04	N/A	NO	YES	
	3	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF PH-BDE (PH)		🟥	🟥	🟥	🟥	🟥	NO	see case NC2.3a
	4	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SSD-WAV		0.82	0.86	0.90	0.981	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SP-WAV		0.90	0.92	0.93	0.981	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	BF LGF SP-WAV		0.87	0.80	0.82	0.978	YES	YES	
	3a	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF PH-BDE (PH)	175 MW refinery	0.82	0.88	0.80	0.986	YES	YES	
REFINERY LOAD IN - Series Compensation on Bay d'Espoir Piper's Hole Lines - CCC														
SC2	1	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF BDE-PH (BDE)		1.00	1.02	1.04		NO	YES	
	2	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF PH-BDE (mid)		1.00	1.02	1.04		NO	YES	
	3	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF PH-BDE (PH)		0.79	0.87	0.88	0.98	YES	YES	
	4	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SSD-WAV		0.88	0.86	0.97	0.981	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	3PF SP-WAV		0.94	0.93	1.00	0.982	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Pipers Hole	BF LGF SP-WAV		0.90	0.89	0.97	0.98	YES	YES	

Summary of Dynamic Performance Results with New 175 MW Refinery Load In-Service

Case		Synchronous Condensers						Min Transient Voltage After Fault clears (pu)			Min Frequency Deviation (pu)	Comm Fail ?	Stable ?	Notes
		Sunnyside SYNCS	SP SYNCHS	Holyrood SYNCHS	Holyrood CT-SYNCHS	Fault	Load Tripped	Sunnyside	Soldiers Pond	Bay d'Espoir				
REFINERY LOAD OUT - No Series Compensation on Bay d'Espoir Piper's Hole Lines - CONVENTIONAL DC														
NC3	1	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (BDE)		🟥	🟥	🟥	🟥	🟥	NO	see case SC3.1
	2	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (mid)		0.87	0.94	0.86	0.980	YES	YES	
	3	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (PH)		0.82	0.94	0.85	0.981	YES	YES	
	4	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SSD-WAV		0.84	0.94	0.93	0.982	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SP-WAV		0.94	0.96	0.95	0.977	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Holyrood	BF LGF SP-WAV		0.83	0.95	0.86	0.971	YES	YES	
REFINERY LOAD OUT - Series Compensation on Bay d'Espoir Piper's Hole Lines - CONVENTIONAL DC														
SC3	1	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (BDE)		0.78	0.92	0.80	0.979	YES	YES	
	2	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (mid)		0.78	0.91	0.85	0.975	YES	YES	
	3	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (PH)		0.86	0.95	0.94	0.982	YES	YES	
	4	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SSD-WAV		0.88	0.94	0.95	0.983	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SP-WAV		0.97	0.97	1.01	0.979	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Holyrood	BF LGF SP-WAV		0.94	0.99	0.99	0.973	YES	YES	
REFINERY LOAD OUT - No Series Compensation on Bay d'Espoir Piper's Hole Lines - CCC														
NC4	1	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (BDE)		0.98	1.005	1.001	N/A	NO	YES	
	2	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (mid)		0.98	1.005	1.04	N/A	NO	YES	
	3	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (PH)		0.85	0.93	0.84	0.978	YES	YES	
	4	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SSD-WAV		0.91	0.92	0.97	0.98	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SP-WAV		0.96	0.95	1.01	0.981	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Holyrood	BF LGF SP-WAV		0.86	0.85	0.94	0.977	YES	YES	
REFINERY LOAD OUT - Series Compensation on Bay d'Espoir Piper's Hole Lines - CCC														
SC4	1	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (BDE)		0.95	0.98	0.92		NO	YES	
	2	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (mid)		0.85	0.86	0.8	0.996	NO	YES	
	3	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF BDE-PH (PH)		0.89	0.85	0.98	0.98	YES	YES	
	4	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SSD-WAV		0.95	0.93	1.01	0.981	YES	YES	
	5	1-300 MIL	1-300 MIL	3	4 @ Holyrood	3PF SP-WAV		0.99	0.95	1.02	0.983	YES	YES	
	6	1-300 MIL	1-300 MIL	3	4 @ Holyrood	BF LGF SP-WAV		0.95	0.93	0.98	0.979	YES	YES	

Summary of Dynamic Performance Results with New 175 MW Refinery Load Out-of-Service

Appendix C

Results for Conventional HVdc with 175 MW New Refinery Load In-Service

Appendices C through F not filed