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February 14, 2020

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

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

Dear Ms. Blundon:

Re: 2019–2020 Winter Readiness Planning Report – Further Update – Bay d'Espoir Terminal Station General Electric Dead Tank Circuit Breaker Failure Report

On December 10, 2019, Newfoundland and Labrador Hydro ("Hydro") filed its "2019–2020 Winter Readiness Planning Report" ("Report") with the Board of Commissioners of Public Utilities ("Board"). In its January 31, 2020 update to the Report, Hydro committed to provide the Board with a technical report addressing the Bay d'Espoir Terminal Station Circuit Breaker Failure issue by February 14, 2020.

Please find enclosed one original and eight copies of Hydro's Bay d'Espoir Terminal Station General Electric Dead Tank Circuit Breaker Failure Report. This technical report summarizes the investigation to date, Hydro's risk mitigation plan, as well as Hydro's recommendations and next steps.

Should you have any questions, please contact the undersigned.

Yours truly,

NEWFOUNDLAND AND LABRADOR HYDRO

Shirley A. Walsh
Senior Legal Counsel, Regulatory
SAW/las

cc: **Newfoundland Power**
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Consumer Advocate
Mr. Dennis M. Browne, Q.C, Browne Fitzgerald Morgan & Avis

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Mr. Denis J. Fleming, Cox & Palmer

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ecc: **Board of Commissioners of Public Utilities**
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Bay d’Espoir Terminal Station
General Electric Dead Tank Circuit Breaker Failure Report

February 14, 2020

A report to the Board of Commissioners of Public Utilities

Executive Summary

Newfoundland and Labrador Hydro ("Hydro") has experienced the failure of four, relatively new, General Electric ("GE") DT1–245P F3 dead tank circuit breakers in over a one-year period. All four failures occurred at Bay d'Espoir ("BDE") Terminal Station 1 ("BDETS1"). This report will outline a summary of each circuit breaker failure and the root cause, as well as the risk mitigation measures being taken by Hydro to prepare for a future circuit breaker failure, and provide recommendations for next steps.

Since October 2018, Hydro has experienced four failures of 245 kV class GE dead tank circuit breakers at the BDETS1. The breakers for three of the four failures were shown to have quality issues from the factory. The root cause of the fourth failure, which occurred on November 17, 2019, is still unknown. This circuit breaker has been replaced and the faulted circuit breaker was sent back to the factory on December 13, 2019. A tear down investigation was completed on January 23, 2020, at the GE factory in Charleroi, Pennsylvania, which was witnessed by Hydro. A root cause had not been identified as of the filing date of this report.

After the third failure on August 24, 2019, of B3T6 at BDE, a focus group was formed between GE and Hydro to help further understand the failures and look at risk mitigation for Hydro going into winter 2019–2020 and beyond. Through this focus group a transient study was recommended and completed, which identified the potential for high voltage (~800 kV) and high frequency (0.7 MHz) transients to occur when the 245 kV unit disconnect switch is operated. As a result of this, effective December 20, 2019, Hydro implemented open circuit breaker flash over protection on the unit circuit breakers for Units 1 to 6 at BDETS1 and changed its operating philosophy when bringing units on and offline to keep the unit disconnect switch closed. This action will help to minimize the risk of a potential circuit breaker failure due to a transient being the failure trigger.

To ensure Hydro can respond quickly in the event of another failure this winter, Hydro has placed two spare circuit breakers at BDETS1. GE has also provided a spreader beam and lifting procedure that will enable the change out of one phase, as all failures to date involved only one of the three phases of the circuit breaker. The outage time to change a complete circuit breaker is estimated to be seven days, while one phase is estimated to take 3–4 days. GE has also committed to providing spare phases in the first quarter of 2020 to eliminate the need to remove a phase from a complete on-hand spare circuit breaker. This is expected to reduce the outage time to 2–3 days.

Hydro has also looked elsewhere on its system and feels the risk is higher for a failure of the GE unit circuit breakers at BDE, but lower at other sites. The rationale being, the unit circuit breakers at BDE see a high number of operations which will generate more particles and also see a higher voltage stress each time a unit is put online or taken offline. The other locations where similar GE breakers are used, are on transmission lines or in bus applications that see few operations and are not typically used for synchronizing where higher voltage stresses will be present. With few operations, less particle generation and lower voltage stress, the risk of failure of a line circuit breaker is lower. Other generating stations, including the Holyrood Thermal Generating Station ("Holyrood TGS"), were also reviewed. These sites were determined to be a lower risk, as these sites have circuit breakers that do not operate as often as BDE, or their circuit breakers are not GE DT1–245P F3, or they have lower voltage circuit breakers for synchronizing.

As of the date of this report, Hydro will not order any further 245 kV class dead tank circuit breakers from GE due to the quality issues identified and the failures experienced. Hydro plans to utilize all 245 kV class GE circuit breakers that have been previously purchased in transmission applications. Also due to the high failure rate at BDE, Hydro plans to look at options to replace the five dead tank GE breakers at BDE (Units 1, 3, 4, 5 and 6) with a circuit breaker that is better suited for generator application and look at using the removed circuit breakers in transmission applications. The review of the options to replace the GE generator circuit breakers at BDE is expected to be completed in the first half of 2020.

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List of Appendices

1.0 245 kV Class Circuit Breaker Failure History at Hydro

This report discusses the investigation of four GE dead tank circuit breakers that failed between the period of October 25, 2018, and November 17, 2019.

The first circuit breaker failure occurred on BDE B2B3, which failed on initial energization on October 25, 2018. The failure resulted from metal filings generated during shipping due to an interrupter exhaust enclosure part being out of tolerance. The second failure occurred on BDE B3T5, which was originally placed in service in 2016 and flashed over across the open contact on A Phase on February 27, 2019. The investigation identified an assembly related issue. The third failure occurred on BDE B3T6, which was placed in-service in 2016 and failed on August 24, 2019. It failed when the generating Unit G6 was being taken offline. When the disconnect switch was being opened, with voltage on both sides of the circuit breaker, the circuit breaker first flashed to ground and then two cycles later flashed over across the open C Phase contact. The investigation identified that a particle was generated from a dimensional non-conformance found on a component of the interrupter. The data collected thus far for the most recent failure of BDE B2T4 on November 17, 2019 is showing a flashover occurred across the open contact during synchronizing, which is similar to the BDE B3T5 failure. This breaker was shipped back to the factory on December 13, 2019 for Failure Analysis and repairs. The tear down investigation took place on January 23, 2020 at the GE factory under the supervision of a Hydro representative. A root cause had not identified as of the filing date of this report.

2.0 Focus Group Creation

After the third failure of BDE B3T6 in August 2019, a focus group was created to help further understand the failures and look at risk mitigation for Hydro going into the winter of 2019–2020 and beyond. The membership of the focus group included:

- Hydro:
    - Hughie Ireland, Manager, Long Term Asset Planning, Terminals and P&C (Co-Chair);
    - Jared Hawco, Electrical Design Engineer, Engineering Services; and
    - Robert Edison, Asset Specialist, Terminals and P&C.

- GE:
  - Tarek El-Farawi, Lead Project Manager, Circuit Breaker Replacement Program (Co-Chair) GE Canada, Point Claire, Quebec;
  - Dinc Otkeren, Manager Customer Care, GE Factory, Charleroi, PA, USA; and
  - Eric Olson, Manager Quality Assurance ("QA") GE Factory, Charleroi, PA, USA.

The focus group first met at the GE Factory in Charleroi, Pennsylvania, USA, from September 24 to 26, 2019 to:

- Witness the teardown of the failed BDE B3T6 circuit breaker and support the Failure Analysis with GE's engineering team;
- Review quality control of the breaker manufacturing at GE's Charleroi, US factory;
- Review the application of GE 245 kV class dead tank circuit breaker design with factory engineers;
- Review testing concerns during Factory Acceptance Testing ("FAT");
- Discuss other utility experiences with GE 245 kV class dead tank circuit breakers; and
- Review transportation methods and possible aggravating effects of circuit breaker transport impacts (i.e. vibration, speed, roads).

Since the factory visit the focus group has continued to meet regularly to get status updates on each of the items listed above. These items, along with a transient study, a summary of risk mitigation for Hydro, and next steps since the fourth failure, will be discussed in separate sections of this report.

2.1 Circuit Breaker Tear Downs and Failure Analysis

2.1.1 Failed Bay d'Espoir B2B3 Circuit Breaker Tear Down and Failure Analysis

GE performed the failure investigation of circuit breaker B2B3 on January 4, 2019. When the interrupter was removed from the tank arc damage was found on the pin side support casting and exhaust enclosure, see Figure 1.

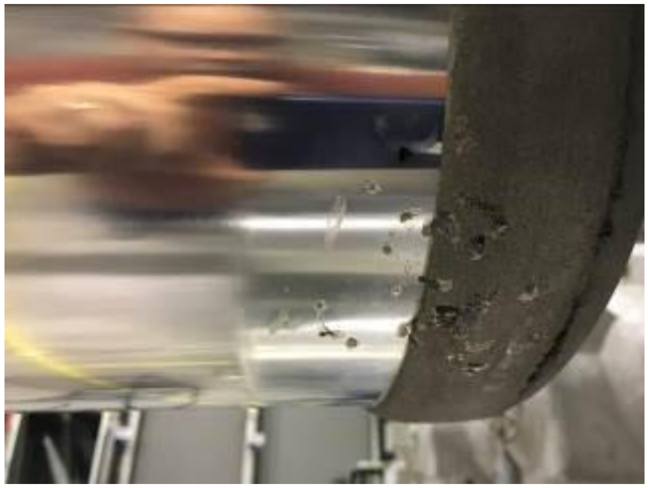

Figure 1: Arc Damage on Interrupter

Arc damage and metal splatter was also found on the bottom of the tank on the pin side directly under the damage to the interrupter. The end casting for the exhaust enclosure was not properly seated as a bolt was not fully engaged. When this casting was removed metallic particles were found inside the exhaust enclosure and the enclosure itself had some scratches due to the relative motion between the parts. See Figures 2 and 3.

Figure 2: Scratches on Exhaust Enclosure

Figure 3: Metal Particles inside Exhaust Enclosure

The evidence found during the investigation strongly suggests that the root cause of the flashover was a dimensional non-conformance of the exhaust enclosure. This prevented the end casting on the pin side from seating properly, which allowed for relative movement between the exhaust enclosure and the casting during transportation to site. This relative movement resulted in damage to the mating parts and produced the metal particles found; this, likely caused the flashover upon initial energization.

2.1.2 Failed Bay d'Espoir B3T5 Circuit Breaker Tear Down and Failure Analysis

GE performed the failure investigation of circuit breaker B3T5 on June 4, 2019, with Hydro representatives present. When the bushings were removed black material was found on the conductors and internal surface of the porcelain, predominantly on the bushing opposite the spring drive. The interrupter was removed from the tank and revealed black material coating most internal surfaces of the tank as well as the interrupter itself, see Figure 4.

Figure 4: Black Material on Interrupter

The bell crank was then removed from the interrupter with no signs of damage to either the bell crank or the corresponding line to ground solid insulation. Upon disassembly of the interrupter, large amounts of black material were discovered on the pin side support casting. This material was collected and prepared for material characterization testing at an external lab.

The interrupter subassemblies were then fully disassembled, which revealed a concentrated amount of black material deposited on the double motion parts between the main nozzle and counter contact cylinder. Thin metallic-like pieces of material were found on the arcing pin, inside the throat of the main nozzle, and inside the counter contact cylinder. The arcing pin showed significant signs of erosion.

It is possible that over the course of several hundred operations the arcing pin became loose and started depositing metal and grease in the nozzle throat. In this case, the voltage withstand capability would degrade and could eventually cause a flashover across the open gap.

2.1.3 Failed Bay d'Espoir B3T6 Circuit Breaker Tear Down and Failure Analysis

GE performed the failure investigation teardown of the BDE B3T6 circuit breaker on September 24, 2019. The faulted C Phase was completed first. There were burn marks noted from the pin side of the interrupter to the tank as well as a blackened gap insulator. The failure theory proposed was a phase-to-ground fault on the pin side due to foreign particles and it developed into a flash over across the open contact, see Figure 5.

Figure 5: Flash To Ground and Across Insulator Gap

From GE's review they have indicated that the initial fault was related to foreign particles inside the circuit breaker tank. Further investigation has identified an area where metal scraping was shown where the gap shield was installed, see Figure 6.

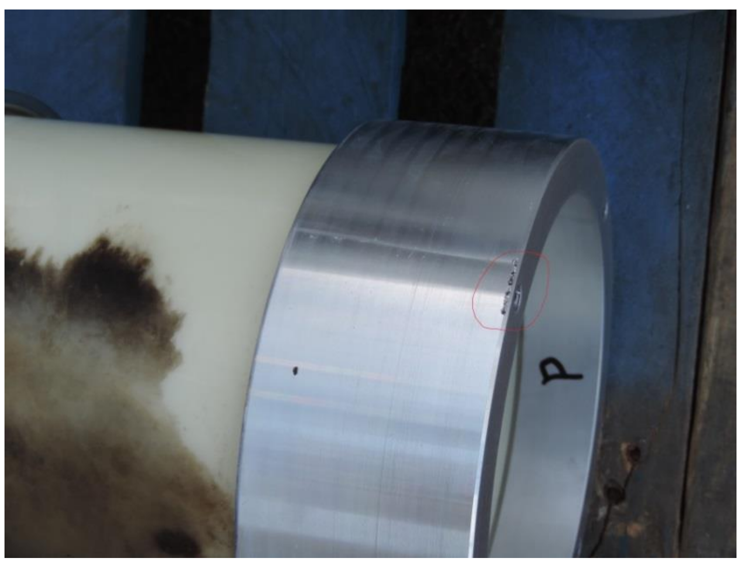

Figure 6: Gap Insulator Flange where Gap Shield was Installed

Particle samples and possible by-product from the SF6 were removed from the tank and interrupter for external lab analysis to determine material content. Also, there was a stink bug which is known to the

Pittsburgh area, found inside the female contact for C Phase center conductor. There was no burning in this area and this did not contribute to the failure.

For B Phase, a bristle from the vacuum used to clean the breaker and some small minor particles were found inside the tank's particle trap, which is designed to catch particles that could be hazardous to circuit breaker operation.

For A Phase, there were minor particles inside the tank, but there was also an oily substance running down the inside of the interrupter sleeve. Lab analysis completed by GE determined that the oily substance was Fomblin UT–18 grease, which is used specifically for friction control on sliding surfaces associated with press fits of interrupter parts. This grease has been tested for the reduction of particle generation and galling of metal on sliding surfaces during pressing operations. The listed temperature range for the grease is -30°C to 150°C. Due to the ship date of the circuit breaker in November 2015 and installation date in June 2016 it is likely that during the winter storage period the ambient temperature reached a point where the oil from the thickening agent (Teflon) began to separate forming oil droplets. From the investigation performed the oil droplets did not cause or contribute to the failure.

As a result of BDE B3T6 failing while taking a unit offline, Hydro confirmed the high level sequence that happened the day the circuit breaker failed. Unit G6 was brought to a low power generation level, which is normal operation prior to opening the circuit breaker, circuit breaker B3T6 was opened, and disconnect switch B3T6–1 was initiated to open. While the disconnect switch was opening there was a phase-to-ground fault that triggered the 87B3 differential protection relay, which initiated the tripping of all Bus B3 circuit breakers including B3T6. B3T6 was passing current due to the flashover across the C Phase insulator so it triggered the breaker failure relay, which shut down unit excitation and tripped the generating unit. See Appendix B for the BDETS1 System Operating Diagram for reference.

Appendix C contains the Relay and Digital Fault Recorder ("DFR") records. The summary presented by Hydro's Protection and Control Engineer aligned with what was witnessed during the teardown.

With this failure being initiated during the opening of a disconnect switch, GE provided further insight into possible high frequency transients during disconnect switching that could amplify problems in the presence of particles. GE provided a study completed as a thesis by a graduate student from BC Hydro discussing the capacitance effects on operation of disconnect switches and the transients formed. Hydro hired Hatch to recreate the B3T6 failure event and complete a transient study to help Hydro understand the potential transients occurring. A meeting took place on October 18, 2019, between Hydro, Hatch, and the GE factory lead engineers to ensure alignment on the scope and methodology of the study.

Hydro reviewed the operating procedure for putting a unit online and taking a unit offline at BDE. One of the items collectively agreed to was the importance of minimizing voltage on both sides of the circuit breaker with the circuit breaker in the opened position. That is, only having synchronizing voltage across the circuit breaker for a minimum time as required to synchronize the circuit breaker.

The sequence of events data confirmed synchronization was being completed between 5–8 minutes, which is a reasonable time. The circuit breaker is designed and tested to withstand 425 kV (approximately 1.5 times the system voltage across the circuit breaker) and should withstand the synchronizing voltage stresses for this duration.

2.2 Quality Control of Circuit Breaker Manufacturing at GE Charleroi Factory

The GE factory in Charleroi, Pennsylvania, USA has an ISO 9001 certified Quality Management System. During the factory visit for the tear down of circuit breaker BDE B3T6 GE discussed improvements made in routine FAT procedures and various manufacturing processes. This section will discuss these items in further detail.

GE tests DT1–245P F3 circuit breakers in accordance with ANSI C37.09, which is specified in Hydro's circuit breaker standard. A summary of the routine dielectric testing completed by GE is as follows:

- Routine high voltage withstand test;
- ANSI test voltage (425 kV) applied is approximately 1.5 times the system voltage across the circuit breaker;
- Voltage applied with circuit breaker SF_6 gas pressure at lockout pressure of 5.1 bar (lowest possible pressure to maintain nameplate ratings); and
- High voltage withstand test is performed after all mechanical testing is completed.

As per the standard, the tests shall be performed in accordance with the requirements of IEEE Std. 4: High Voltage Testing Techniques and the voltage shall be applied to the terminals of the circuit breaker for a duration of one minute, in any desired order, under the following conditions:

- With the circuit breaker contacts open, apply the specified test voltage to each terminal of the circuit breaker individually with all other terminals and the frame of the circuit breaker grounded (Across open contacts); and
- With the circuit breaker contacts closed, apply the specified test voltage to each phase of the circuit breaker individually with the other phases and the frame of the circuit breaker grounded (Line to ground).

All circuit breakers that experience a flashover during routine high voltage withstand tests are pulled back into production and opened for investigation by QA to determine root cause. In the event of a problem, the Test Lab initiates an Internal Quality Concern Report ("IQCR") to document the issue experienced during testing. QA reviews the IQCR with the investigation findings for correction, recording, and trending analysis.

2.2.1 General Electric Manufacturing Improvements for Circuit Breaker DT1–245P F3

The following are notable manufacturing improvements being implemented by GE:

- GE are in the final stages of implementing a pneumatic device to operate interrupters on DT1–245P F3 circuit breakers prior to installation of the interrupter inside the circuit breaker tank enclosure. GE already has this procedure for 72.5 kV and 138 kV breakers. This will allow for a wear-in period of the interrupter guide bands and contact running surfaces outside of the tank enclosure and minimize particle creation inside the interrupter and tank. This enables:
    - Cleaning and inspection of interrupters; and
    - Assembly check prior to operation.
- GE part design improvements as a result of BDE B2B3 Failure Analysis findings.
    - GE inspected all exhaust covers in stock to check for other non-conformances, but all parts were found to be within specified tolerances. The supplier was notified of the non-conformance. An engineering action request was created, which resulted in a small adjustment to the exhaust cover tolerance; and
    - GE also implemented a new tool (go/no go gauge) in the interrupter production line to verify the assembly is correct.
- GE QA document improvements as a result of BDE B3T5 Failure Analysis findings.

  - GE added additional steps to their Interrupter Control Checklist to verify and stamp that the arcing pin has been properly torqued and Loctite thread lock has been applied.

While at the factory Hydro witnessed the assembly of the new interrupter that replaced the failed interrupter in the repaired BDE B3T6. No concerns were noted.

2.2.2 Internal Audit Process for ISO 9001

GE provided a review of their Quality Management System and Audit Process. Hydro requested and received a copy of the internal audit report that was completed prior to the registration audit. Several observations were recorded in the internal audit, but nothing significant was noted.

2.3 Review the Application and Design of GE 245 kV Class Dead Tank Circuit Breakers

While at the factory, the application of circuit breakers in Hydro's system was reviewed with the GE Engineering team. GE Engineering provided a presentation on the standards the circuit breakers are manufactured to and the testing required for Type and Routine Tests. It was indicated that generator duty (as a result of synchronizing) results in higher stresses on a circuit breaker than a terminal station bus breaker, but the breaker is designed and tested to withstand 425 kV (which is approximately 150% higher than two times the line to neutral voltage that the circuit breaker normally sees during synchronizing).

It was noted; however, that one of the biggest issues with dead tank circuit breakers is eliminating particles due to the manufacturing and assembly process. In fact there are particle traps built into the circuit breaker tank design. As a result, generator circuit breakers will potentially see problems due to particles inside the unit sooner than a transmission line or terminal station bus circuit breaker. This is due to the increased number of operations and exposure to higher voltages across the open circuit breaker during times a generating unit is brought online or being taken offline.

2.3.1 Dead Tank vs Live Tank Circuit Breaker Design

Outlined in this section are the main pros and cons associated with dead tank and live tank circuit breakers.

Dead Tank Circuit Breakers:

Pros:

1. Very small foot print;
2. Internal bushing CT's for protection and measurement – up to three per side;
3. Smaller phase spacing; and
4. Lower center of gravity.

Cons:

1. Prone to line to ground flashovers due to nature of design – live interrupter and grounded tank;
2. Particle sensitivity issues – can lead to flashover;
3. Higher quantity of gas, more surface area, and porosity of castings can all contribute to more gas leaks;
4. Continuous solid insulation degradation due to high voltage stresses because of grounded tank; and
5. High shipping stress can lead to invisible micro cracks in parts.

Live Tank Circuit Breakers:

Pros:

1. Lower quantity of gas (~15–20% volume of dead tank) and less prone to leaks;
2. No possible arcing between chamber and tank (all at live potential);
3. Can withstand line-to-ground voltage even after some gas loss;
4. Common failure modes almost absent – very low failure rate for GE live tank circuit breakers in service since 1999 (0.20%); and
5. Particle related failure is rare due to vertical nature of tank.

Cons:

1. Bigger foot print, higher phase spacing;
2. External CT's required for protection and measurement;
3. Mechanical failures can happen;
4. Central control cabinet required; and
5. Higher center of gravity;

2.4 Factory Acceptance Testing

While at the factory GE provided Hydro FAT data for three randomly selected circuit breakers. Hydro reviewed quality and routine test documents from randomly selected circuit breakers and noted details were signed off and stamped as per procedures.

From this review Hydro recommended the improvements in process as a result of the two most recent 245 kV class circuit breaker failures be applied to 145 kV and 72.5 kV class breakers.

2.5 Other Utilities Experience with GE 245 kV Class Dead Tank Breakers

Since 2010, GE has supplied 245 kV class dead tank circuit breakers to BC Hydro (15), Hydro Quebec (21), Manitoba Hydro (2), Saskatchewan Power (4) and low quantity units to others (71). In the United States, the client list includes the City of Boulder, CBK Power Company, Lafayette Utilities System, Powersouth Energy Cooperative, the City of Alexandria and more.

Hydro followed up with BC Hydro, Manitoba Hydro, and Hydro Quebec to discuss their experience with GE 245 kV class dead tank circuit breakers and has documented the findings in the sections to follow.

2.5.1 BC Hydro

- Many GE DT1-72.5FK circuit breakers in service:
  - No in service or major catastrophic failures of this circuit breaker type; and
  - Some issues with leaks and corrosion.
- Many GE GLX live tank circuit breakers at 550 kV, no issues after many years in service;
- Few GE 145/245 kV dead tank circuit breakers:
  - Purchased 15 units since 2010 – all independent pole operation ("IPO"), -50°C rated with mixed gas for locations in the mountains;
  - All units are in substations as bus or line breakers; and
  - No issues with these circuit breakers after seven years in service other than those noted below.
- They had three failures of GE 245 kV mixed gas circuit breakers in roughly a two-year period. With the mixed gas design GE has indicated the interrupter is a different design than the one used in an SF_6 (not mixed gas) design:

  - First failure occurred on initial energization. Failure Analysis revealed that the interrupter had shifted inside the tank during transportation causing an internal flashover. Upon discovering this BC Hydro opened the tanks on a number of circuit breakers and found the same issue with some other interrupters, which were subsequently repaired;
  - Second failure also occurred on initial energization. During one of the interrupter repairs an item was left inside the tank before it was closed, causing an internal flashover upon energization; and
  - Third failure occurred on a circuit breaker that was in-service for about two years due to an internal line to ground flashover. Failure Analysis revealed that flashover was likely due to particle inside Interrupter Insulator 2. Exact source of particle undetermined, but likely due to break-in period of interrupter.
- BC Hydro is very concerned about impacts of road transportation by truck on dead tank circuit breakers, especially when traveling long distances to remote locations with poor road conditions and when circuit breakers change trucks during shipment. The interrupter is different in an IPO dead tank circuit breaker – the cantilever design more prone to transportation issues;
- BC Hydro using ABB HPL mixed gas live tank circuit breaker for generator application:
  - Most generation at 550 kV, compared to 230 kV for Hydro;
  - No dead tank circuit breakers on generators at 245 kV; and
  - No conscious decision to use live tank over dead tank for generator application as dead tank circuit breakers are just as capable and rated to withstand all requirements of switching, transients, etc. Decision to use live tank circuit breakers based on other factors:
    - -50°C rated using mixed gas without tank heaters. They have experienced issues with tank heaters in the past;
    - Fault levels; and
    - Market availability and cost effectiveness.
- BC Hydro performs a manufacturer review for all major equipment, including circuit breakers, every five years to ensure they are getting the best technology available on the market for their needs;

- BC Hydro indicated that having multiple failures at one terminal station in such a small time frame is very serious and unusual. Their opinion is that the high frequency of failures indicates some sort of systemic issue, as opposed to an isolated issue, being caused by:
    - Transportation issues between the factory and site;
    - Design/Manufacturing/Quality issues;
    - Application issue; and
    - Some combination of the above.
- Due to multiple failures during synchronization or taking a generator offline it is very likely that we have a systemic issue at the BDS terminal station that is aggravating other issues, to the point of failure, caused during manufacturing or transportation.

2.5.2 Manitoba Hydro

- Many GE DT1-72.5FK circuit breakers in service
    - No in-service or major catastrophic failures of any GE circuit breakers
    - Some issues with leaks and corrosion
- Very few GE 145/245 kV class dead tank circuit breakers
    - Purchased only two units since 2013 – both 245 kV, IPO, -50°C rated with mixed gas. No issues with these two units.
    - Using other manufacturers due to superior cold temperature testing
    - All units are in substations as bus or line circuit breakers
- 145 kV voltage class: ABB PM series – dead tank circuit breaker
- 245 kV voltage class:
    - Gang-operated: Mitsubishi Electric Power Products Inc. ("MEPPI")
    - IPO: MEPPI + POW ("Point on Wave") Controller
- Experienced some failures of circuit breakers in reactor switching applications
- Experienced particle related failure on ABB circuit breaker. Found copper slivers inside the tank likely created from a die used in the manufacturing process

- Manitoba Hydro has generation at both 145 and 230 kV. Using predominantly live tank circuit breakers, but do have some tank circuit breakers for areas with lower fault levels.
    - Like BC Hydro there was no conscious decision to use live tank over dead tank for generator application. Decision to use live tank circuit breakers based on similar factors:
        - -50°C rated using mixed gas without tank heaters. They have experienced issues with tank heaters in the past;
        - Fault levels; and
        - Market availability and cost effectiveness.
- Manitoba Hydro typical generating station setup is different than Hydro's BDE station in that they use a low voltage unit circuit breaker and the generator step up ("GSU") transformer is only separated from the ring bus by a motorized disconnect switch ("MOD"):
    - Manitoba Hydro: Generator – Unit circuit breaker (Low voltage) – GSU – MOD – Ring bus;
    - Hydro BDE Station: Generator – GSU – 245 kV unit circuit breaker – MOD– Ring bus; and
    - Manitoba Hydro high voltage "generator breakers" are the bus circuit breakers on the ring bus.

2.5.3 Hydro Quebec

- All circuit breakers certified and tested for all applications; line, transformer, bus, capacitor bank, and generator;
- Use both dead tank and live tank circuit breakers for all applications;
- Most generating stations just have medium voltage circuit breaker on generator;
- At least one plant with high voltage circuit breaker on the high side of unit transformer. At that plant they have 5 x 145 kV MEPPI – dead tank circuit breakers installed 2010–2018. No issues with these circuit breakers;
- No GE DT1–245 circuit breakers on generators;
- DT1–245 final assembly completed at La Prairie plant until it shut down. Hydro Quebec Quality Inspector would inspect factory and QA policies before accepting circuit breakers during routine FAT testing;
- Two known failures on GE dead tank circuit breakers:

  - DT1-245 failure caused by improperly installed rupture disk; and
  - DT1–145 failure caused by pollution on the bushing.
- 700 kV are all live tank circuit breakers;
- 69–245 kV are typically dead tank circuit breakers, mostly GE and MEPPI.

2.6 Transportation

This section examines the possible aggravating effects of transportation impacts (i.e. vibration, speed, roads) on the circuit breaker.

The typical transit time from the GE Charleroi Factory is between 5 to 7 calendar days but ten days is typically scheduled to account for any potential delays, mainly at the ferry crossing. Arrival times are revised as the circuit breaker crosses into Newfoundland and the persons receiving the circuit breaker are notified 24 to 48 hours prior for accurate arrival time. In terms of trailers, GE only uses mini-deck equipment, as these are needed to ensure overhead clearances. All transports used to ship the dead tank breakers are equipped with air ride suspensions. There have been two transporters used during the GE circuit breaker replacement program to ship the circuit breakers; Patco Transports and Golden International. Both have been long-time trusted partners to GE Canada and are used for many other high voltage equipment shipping.

The typical routing is approximately 3000 km. The main route selected, starting from Charleroi, is to drive east through New York state. The circuit breaker passes through the Montreal area and continues to North Sydney to embark on the ferry crossing. All roads up to this point are paved State and/or Provincial highways. The truck crosses on the ferry to Port aux Basques, and then continues to the pre-determined final location (Bishop Falls or specific terminal station). Throughout the entire transit, the circuit breaker stays on the same mini-deck trailer and is never transferred while in transit. Up until BDE B3T6 failure no impact recorders were used.

GE has an engineering drawing of how the circuit breakers are to be configured on the truck. The trucks used are special low bed trucks with air ride suspension. The circuit breakers are strapped down by the driver of the truck under the supervision of a person from the GE factory. For new designs, a part of the type testing is to complete a road test with the new circuit breaker design.

To help better understand any transportation concerns GE applied an impact recorder when shipping the repaired B3T6 circuit breaker back to BDE in Dec 2019. The impact recorder was then transferred to the failed B2T4 circuit breaker for the return trip to the GE Charleroi factory. There were no significant findings noted from the impact recorder data for the trip in December 2019. However, it should be noted that the road conditions on the BDE highway have been significantly improved since the unit circuit breaker replacements in 2015 and 2016.

2.7 Bay d'Espoir Operational Philosophy for Starting and Stopping Units

During a unit start-up, the high side disconnect switch is given a close command by the operator at BDE that, once closed, places 230 kV bus voltage on one side of the circuit breaker. After closing the unit disconnect switch, the operator initiates a start of the unit. The unit runs up to speed and the field is flashed[1] at 95 % of synchronous speed. This will result in the unit side of the circuit breaker becoming energized. The automatic synchronization is then initiated and the circuit breaker is closed when alignment with voltage, phase angle, and frequency are met. This procedure can take up to eight minutes.

When a unit is taken offline, the Energy Control Center operator will unload the unit down to 2 MW or less and then open the circuit breaker. The operator at BDE will then open the disconnect switch and give the unit a stop command. When the unit is given the stop command the excitation voltage is lost immediately.

2.8 Hydro's Review of GE 245 kV Class Circuit Breakers at Other System Locations

After the four failures of 245 kV class GE dead tank circuit breakers at BDE, Hydro completed a review of its system to determine other locations with the same GE 245 kV class dead tank circuit breakers. A list of installed GE DT1–245P F3 dead tank circuit breakers in Hydro's system is included in Appendix D.

In evaluating the risk of a future failure Hydro has considered the following:

- Since 2015 Hydro has replaced 27, 245 kV class circuit breakers with the GE DT1–245P F3 dead tank circuit breaker, five of which are in a generator application and the other 22 are in a bus or line application;

[1] Field flashing is used on generators where the residual magnetism is not high enough to build up the terminal voltage during start-up. It is done by connecting an external direct current source from an exciter to the field winding to start the voltage build up.

- Generating unit circuit breakers at BDE have a large number of operations due to the units being operated as peaking units. As a result of the number of operations, these circuit breakers will be prone to more particle generation;
- Generating unit circuit breakers are exposed to higher voltage stresses during synchronizing (two times the line to ground voltage);
- Generating unit circuit breakers at BDE are exposed to transient voltages and currents due to the switching of the high side disconnect switch;
- The generator circuit breakers were considered the most critical and the higher risk to the system, due to their ability to prevent generation energy from getting onto the system;
- Transmission circuit breakers do not operate frequently, are less prone to particle generation, and are not normally exposed to two times the line to ground voltage across the circuit breaker during synchronizing;
- There is no redundancy for unit circuit breakers 1 to 6 at BDE. There is only one circuit breaker between the generating unit and the system;
- The following generating plants use 245 kV class circuit breakers to synchronize generating plants, but do not use GE dead tank circuit breakers: Cat Arm (MEPPI) and Holyrood TGS (Siemens); and
- The following generating stations synchronize using lower voltage circuit breakers on the low side of the GSU transformer: Upper Salmon, Granite Canal, Hinds Lake, Star Lake, and Exploits.

2.9 Breaker Failure Study (Referenced as Transient Study)

As a follow up from the recommendations from the GE factory engineers, Hydro engaged Hatch to complete a transient study at BDE. This study was carried out from October to December 2019, with the final report issued by Hatch on January 28, 2020 ("Transient Study"), [2] provided as Appendix A. The findings of the study show that the switching of the high side 230 kV disconnect switch can create a high frequency transient voltage over 700 kV. This transient level is below the design limit of 1050 kV, but still high enough to possibly cause movement of particles inside the circuit breaker. The particles could potentially move from an area of low electrical stress to an area of high electrical stress, which could reduce the voltage withstand of the circuit breakers and trigger an internal flashover.

[2] Hatch, "Breaker Failure Study," January 3, 2020.

A recommendation from the transient study is to replace the Capacitive Voltage Transformers ("CVTs") at BDE Buses connecting generation to the system with Potential Transformers ("PTs"). This will reduce the capacitance ratio and significantly reduce the transient created during operation of the disconnect switch.

Due to Hydro's current 230 kV standard for voltage sensing being CVTs, Hydro does not have 230 kV PTs in stock and the delivery will be in the order of 24 to 34 weeks. As a result, further review was completed of Hydro's operating philosophy to determine if the unit 230 kV disconnect switch can remain closed. From this review it was determined that with the 230 kV unit disconnect switch closed, the unit offline, and the unit circuit breaker in the open position, there currently is no protection for the transformer or the generator unit to clear a circuit breaker flashover.

To allow Hydro to keep the 230 kV unit disconnect switches closed and eliminate the transient, Hydro implemented open circuit breaker flashover protection on the circuit breakers for Units 1 to 6 at BDE as of December 20, 2019. Effective the same date, an operating philosophy change was made to ensure the 230 kV unit disconnect switch remains closed when units are put on and taken off the system.

3.0 Risk Mitigation for Hydro

Since October 2018 Hydro has experienced four failures of DT1–245P F3 dead tank circuit breakers at BDETS1. Three of the four failures have shown to have quality issues from the factory and the root cause of the fourth failure, which occurred on Nov 17, 2019, is still unknown.

After the third failure, which occurred on August 24, 2019, Hydro and GE formed a focus group made up of three representatives from each side to help mitigate Hydro's risk of a another circuit breaker failure.

To help with risk mitigation for Hydro and to ensure Hydro is well prepared for another failure the focus group has initiated the following:

1) GE has repaired all failures up to this point at their factory at GE's expense;
2) GE extended the warranty by two years for its circuit breakers and has covered the cost of repairs at its factory for the first three failures. GE will decide if the fourth breaker will be covered once the investigation is completed on the latest failure;

3) GE provided a procedure on December 10, 2019, to change out one phase of the circuit breaker to expedite the return to service of a unit circuit breaker at BDE in the event of a failure throughout this coming winter;

4) Due to the failures happening at BDE, Hydro has the repaired circuit breaker from B3T6 placed in BDE to enable either a phase to be removed and installed or the complete circuit breaker to be replaced;

5) An impact recorder was used for the shipment of the repaired B3T6 circuit breaker, which left the GE factory on December 4, 2019, and arrived at BDE on December 13, 2019, to help determine if transportation is a concern for these circuit breakers. There were no significant findings noted from the impact recorder data;

6) The operating sequence for putting a unit online and taking a unit offline was reviewed. From this review it was determined that the operators place units on line and offline efficiently, which minimizes the amount of time the circuit breaker sees extra voltage stress (two per unit voltage) across the circuit breaker. Essentially the circuit breaker is designed for the application. This review did not consider the transients;

7) Due to the failure of BDE B3T6 occurring when the unit disconnect switch was opening GE's engineering team recommended completion of a Transient Study of the BDE Terminal Station. Hydro hired Hatch to complete this study and it was determined there were high transients occurring from switching the unit disconnect switches, but the values were below the rating of the circuit breakers. However, due to the combination of the transient from the switching, particles in the circuit breaker from quality issues, and the increased voltage stress (two times line to ground voltage across circuit breaker) during synchronizing, Hydro changed its operating philosophy to keep the 230 kV disconnect switch closed. Prior to making that change Hydro implemented open circuit breaker flashover protection to ensure a flash over on one phase will be detected quickly to minimize any damage to the transformer or the unit if the circuit breaker were to fail with the generating unit offline;

8) Hydro followed up with other Canadian utilities to get their experience and the application for the use of the same 245 kV class GE dead tank circuit breakers. Other utilities have seen fewer failures but do not use these circuit breakers in a generator application. They use either live tank design (due to interrupting capability requirements) or use a lower voltage circuit breaker to synchronize generation to the system;

9) To help mitigate the risk going into winter 2019–2020 the focus group recommended internal inspection of circuit breakers installed in 2016,that would have had a significant number of operations and potential particle generation inside their tanks. A plan was developed to inspect B1T1, B2T3, and B2T4 circuit breakers at BDE. A GE factory technician went to BDE and completed the internal inspection of B2T4 on November 16, 2019, and when the circuit breaker was restored to service on November 17, 2019, it failed on A Phase. Further inspections were cancelled;

10) GE will provide at no cost to Hydro in the first quarter of 2020, three separate spare phases to install in either of the A, B, or C positions to help expedite the return to service of a future failed circuit breaker; and

11) Hydro has also looked elsewhere on its system and feels the risk is high for a failure of the GE unit circuit breakers at BDE, but is lower at other sites. The rational for this is that the unit circuit breakers at BDE see a high number of operations and also see a higher voltage stress every time a unit is put online or taken offline. The other locations where similar GE circuit breakers are used are on Transmission lines that see few operations and are not typically used for synchronizing. With fewer operations, particle generation, and lower voltage stress the risk of failure of a line circuit breaker is lower. Other generating stations including Holyrood TGS were also reviewed and determined to be a lower risk, as these sites have circuit breakers that do not operate as often as BDE, or their circuit breakers are not GE, or have lower voltage circuit breakers for synchronizing.

With the high rate of failure Hydro is seeing at BDE, Hydro will look at other options to consider replacing five dead tank GE circuit breakers at BDE (Units 1, 3, 4, 5 and 6) with either a live tank design or another circuit breaker design that is better suited for generator application. This review will be completed in the first half of 2020.

4.0 Key Findings and Actions Taken

1) The design of dead tank circuit breakers is prone to issues with particles generated in the manufacturing and general operation of the circuit breaker. The circuit breaker is designed to have particle traps to catch any foreign particles that end up inside the tank (after manufacturing, transportation, and operation);

2) Generator circuit breakers have more operations (greater chance of more particle generation) and have a higher electrical stress during synchronizing;

3) Hydro has had 4 failures of GE 245 kV class circuit breakers that are installed at BDE. Three of the four were associated with generator circuit breakers (B3T5 February 2019, B3T6 August 2019, and B2T4 November 2019). The other failure was on bus breaker B2B3 in October 2018;

4) The investigations completed on three of the circuit breakers that failed found that all had quality concerns.

   Circuit breaker B3T6 failed when the circuit breaker was in the open position with voltage on both sides, and the unit disconnect switch was in the process of being opened. Due to the failure occurring during opening of the disconnect switch, Hydro had further discussion with GE Engineering and Hydro engineering on this transient phenomenon that occurred and completed a transient study at BDE. Results from the study showed there could be transients over 700 kV.

   The GE dead tank circuit breakers are designed to withstand transients at this level but with particles inside the circuit breaker and transient voltages there is a greater chance of failure. Implementing open circuit breaker flash over protection and changing the operating instruction to keep the 230 kV unit disconnect switch closed will mitigate this risk;

5) Through a review Hydro confirmed generating units at BDE are placed online and offline line in a reasonable time frame to minimize the time the circuit breaker is seeing voltage in the open position; and

6) BC Hydro has expressed concern with the forces exerted on dead tank circuit breakers during transportation, especially to remote sites. This is based on the failure of two GE IPO dead tank circuit breakers due to the interrupter becoming loose during shipment. It should be noted that the interrupter design for this type of circuit breaker is different than the GE DT1–245P F3 circuit breaker installed by Hydro and is more prone to issues during transportation. BC Hydro has also experienced the failure of one of these circuit breakers due to an internal line to ground flashover likely caused by a particles created during the break-in period of the interrupter. Manitoba Hydro has also experienced a particle related failure on a 245 kV class dead tank circuit breaker made by another manufacturer as well as multiple failures in a reactor switching application. This would be similar to a generator application as the circuit breakers are frequently operated and are exposed to higher voltage stresses. Hydro Quebec has experienced

failures on two GE 245 kV class dead tank circuit breakers; one due to an improperly installed rupture disk and another due to pollution on a bushing.

5.0 Recommendations and Next Steps

As of the date of this report, Hydro will not order any further 245 kV class dead tank circuit breakers from GE due to the quality issues identified and the failures experienced. Hydro plans to utilize all 245 kV class GE circuit breakers that have been previously purchased in transmission applications where the risk of failure is lower. Also due to the high failure rates at BDE, Hydro will look at options to replace the five Dead Tank GE circuit breakers at BDE (Units 1, 3, 4, 5 & 6) with a circuit breaker that is better suited for generator applications and consider using the removed circuit breakers in transmission applications. The review of the options to replace the GE generator circuit breakers at BDE will be completed by the end of the third quarter 2020.

By the end of the third quarter 2020, Hydro also will review whether it will proceed with changing out the CVTs in BDE with PTs and change the operating philosophy back to operating the 230 kV high side disconnect switch when putting a unit at BDE on and offline.

Appendix A

Hatch Breaker Failure Study

HATCH

Newfoundland and Labrador Hydro (NLH)
Bay D'Espoir Terminal Station#1
H361486

Engineering Report
Engineering Management
Breaker Failure Study

Report

Breaker Failure Study

H361486-00000-200-230-0001

			E.Karimi	[signature]	[signature]	
2020-01-03	B	Client Review	E. Karimi	V. Pathirana	V. Pathirana	Not Required
DATE	REV.	STATUS	PREPARED BY	CHECKED BY	APPROVED BY	APPROVED BY
				Discipline Lead	Functional Manager	Client

H361486-00000-200-230-0001, Rev. B,

Ver: 04.03

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Newfoundland and Labrador Hydro (NLH)
Bay D'Espoir Terminal Station#1
H361486

Engineering Report
Engineering Management
Breaker Failure Study

1. Introduction

Hatch was retained by Newfoundland and Labrador Hydro (NLH) to assist in the investigation of breaker failure at Bay D'Espoir (BDE) Terminal Station #1.

Breaker B3T6 failed on 8/24/2019 at the time of operation of the B3T6-1 disconnect switch. Figure 1-1 shows the single line diagram of the interconnection of Generators 5 and 6 in BDE TS#1. In a meeting with the manufacturer of the breaker, GE, the transients created during disconnect switch operation as well as the role of particles inside the breaker in reducing the effective withstand capability of the breaker have been discussed. NL Hydro requested Hatch to carry out a study to recreate the switching transients created during disconnect switch operation. As all the breakers at BDE have now been replaced with the GE dead tank design which are prone to generating particles inside the breaker, one objective of the study is to investigate ways to minimize the transients generated during disconnect switch operation.

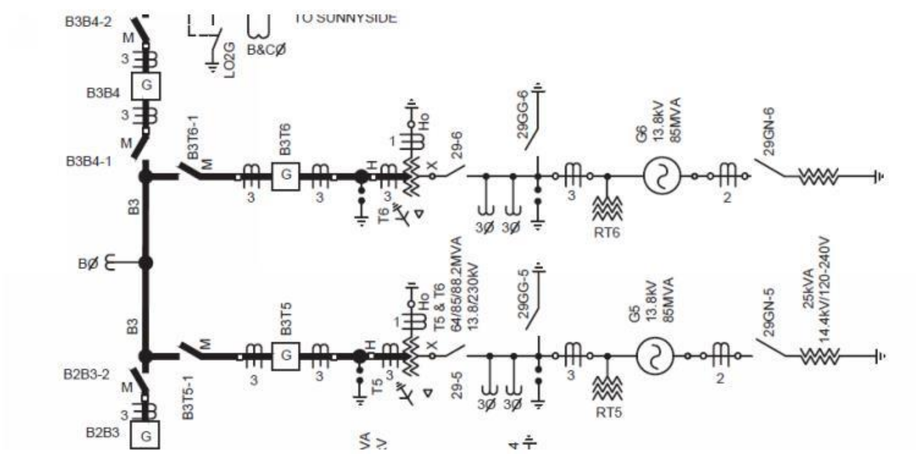

Figure 1-1: Configuration of Interconnection of Breaker B3T6 and Disconnect Switch B3T6-1 in BDE TS#1

Hatch's scope of work includes performing simulations of the NLH system around BDE stations in PSCAD. The simulations are used to recreate the failure event and also to investigate the generation of high frequency transients during disconnect switch operation. A mitigation method is investigated for the reduction of the switching transients.

It should be mentioned that the simulations are fact finding in nature and may not exactly recreate the actual failure, rather give insight into what is happening.

This report summarizes the simulations and the analysis performed by Hatch.

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2. Methodology

Hatch has taken the following steps in order to investigate the failure:

- Reviewing the fault traces and data
- Developing the PSCAD model of the system
- Performing simulations as required
- Investigation of mitigation method/s.

2.1 Review of the Fault Traces

Review of the fault traces obtained from protection relays on Transformer T6, the breaker and Generators 5 and 6 show development of two faults during operation of the disconnect switch. Figure 2-1 illustrates the current waveforms seen by relays on high voltage side of the transformers T5 and T6. Waveforms labeled "X" are on G5/T5 branch and those labeled "Y" are related to the G6/T6 branch. As per the fault traces, the initial fault (a flashover to the ground) only affects generator G5, which contributes to the fault current. After almost two cycles, the second fault (contact to contact flashover of breaker B3T6) affects the G6 and current starts flowing in B3T6. After 3 cycles from the first fault, the bus protection operates, isolating bus B3 and G5 from rest of the system (breakers B3T5, B2B3 and B3B4 are opened). However, G6 keeps contributing to fault current. Based on the waveforms, both faults are at 230 kV level on phase C.

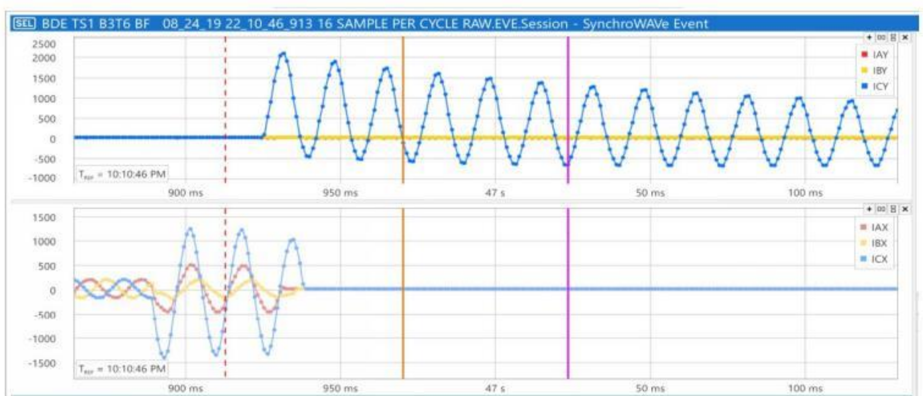


Figure 2-1: Waveforms Obtained from Breaker Failure Relay (Located on High Side Bushings of T5 and T6)

Figure 2-2 shows the waveforms seen from Generator 6 relay. The current waveforms are seen from 13.8 kV side (delta side) of the delta-wye transformer. The voltage and current waveforms show that G6 starts contributing to the fault current two cycles after the initial fault.

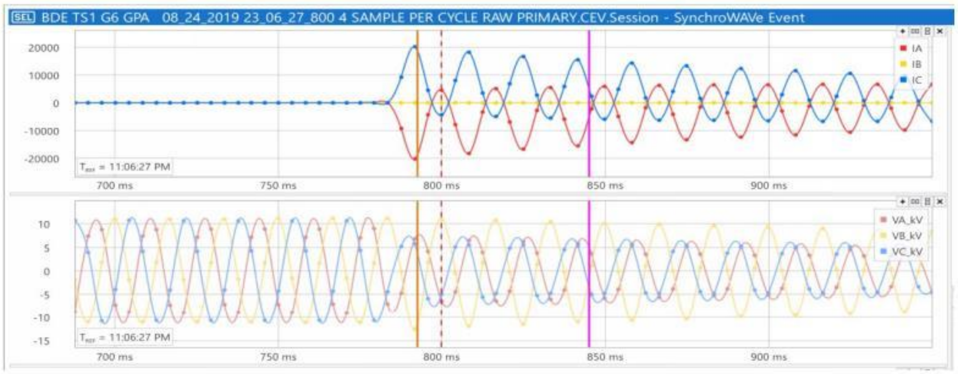


Figure 2-2: Waveforms Obtained from Generator G6 Relay

2.2 PSCAD Model of the System

The PSCAD model of the BDE TSs #1 and #2 is developed based on the model provided in PSSE software. The main focus of the study is bus B3 in BDE TS1, where G5 and G6 are connected to B3, as shown in Figure 2-3.

To investigate the transient behaviour of system during switching of motor operated disconnect, accurate representation of all system parameters is required. This includes modeling of stray capacitances of all components, such as transformers, breakers, switches, CTs, PTs, CVTS, etc. These values can be determined by measurements or calculation and are usually available in equipment test reports. In the case where data is not available, IEEE Std C37.011 provides a guide for estimating the effective capacitance of various apparatus.

2.3 Simulation Cases

2.3.1 Recreation of Fault Incident

Using the developed PSCAD model and based on the received fault trace data, the fault events are recreated. Figure 2-4 depicts the comparison between actual fault traces obtained from relays and the recreated fault event using PSCAD model. As it can be seen, PACAD simulations are able to fairly accurately recreate the fault scenario.

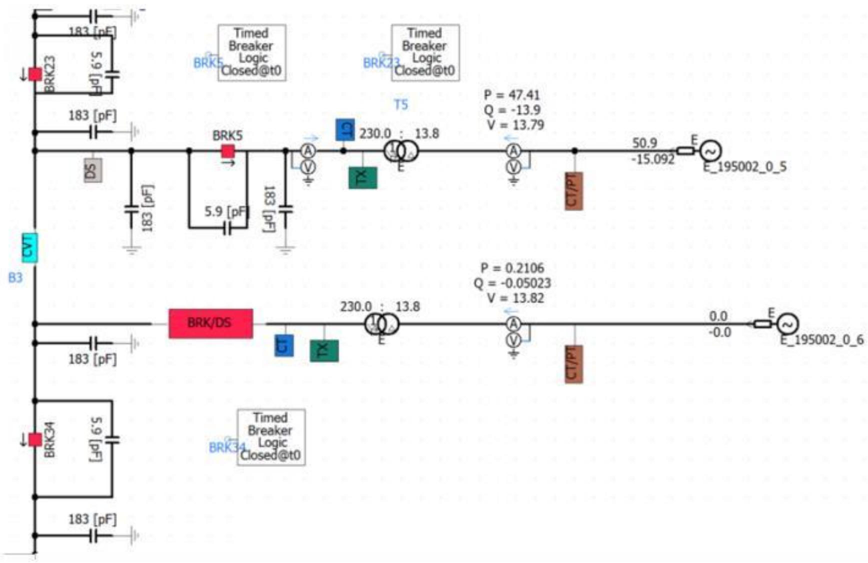


Figure 2-3: Schematic of Developed Model in PSCAD

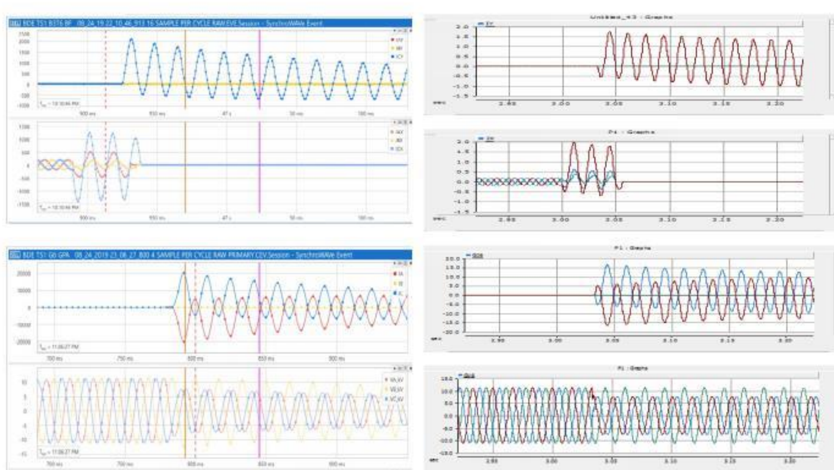


Figure 2-4: Simulation of Fault Event in the Developed Model in PSCAD

2.3.2 *Investigation of Main Reasons for Flashover*

To investigate the main cause of the flashovers in more detail, a study is conducted using an approximate equivalent model of the circuit. In doing so, an approximate equivalent of the system from breaker connection point all the way up to the bus (B3) is developed considering all the capacitance and inductance values of the equipment. This is to investigate the impact of the induced effect during occurrence of a disturbance in the system. It is assumed that the capacitive, inductive and resistive elements of the circuit can be approximated on both sides of the disconnect switch, as shown in Figure 2-5. In this circuit, C_N and C_E are the equivalent capacitance values on each side of the disconnect switch, L_T is the equivalent loop inductance and R is the arc resistance value.

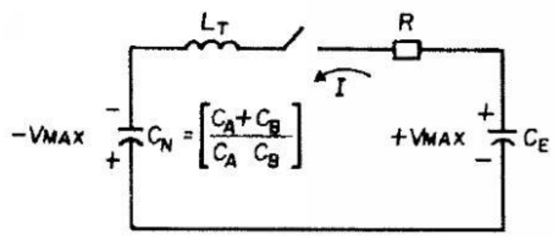


Figure 2-5: Approximate Equivalent Circuit[1]

During disconnect switch is opening, capacitors are left with a trapped charge. In the worst case scenario, the voltage on one side of the switch will be equal to +Vmax and the voltage on the other side will be -Vmax. Because of arcing of the disconnect switch, this trapped charge will be dissipated in the circuit creating transient currents and voltages across the elements. These transient voltage and current components have high frequencies, in the order of hundreds of kHz to MHz ranges. If this transient voltage that appears across the bushings of the breaker is higher than its withstand capability, a flashover may occur causing the breaker to fail.

The major components with shunt capacitance to the ground on the breaker side of the disconnect switch are the breaker bushing, CT capacitors and the disconnect switch stray capacitance. However, at the bus side of the disconnect switch, CVTs (single phase and 3 phase), breakers, disconnect switches and CTs all contribute together creating a much larger capacitive impact compared to the breaker side of the disconnect switch.

Figure 2-7 shows the approximate equivalent circuit of the circuit connections from the breaker B3T6 up to the main bus. This event is perceived as a local event, thus it is mainly impacted by the equipment in the vicinity of the disconnect switch. For the capacitances of

[1] W.C. Kotheimer, "Control Circuit Transients", GE Power management, GER-3061.

the CVTs, the two 3-phase CVTs on lines TL202 and TL204 and two single Phase CVTs on buses B3 and B2 have been taken into account.

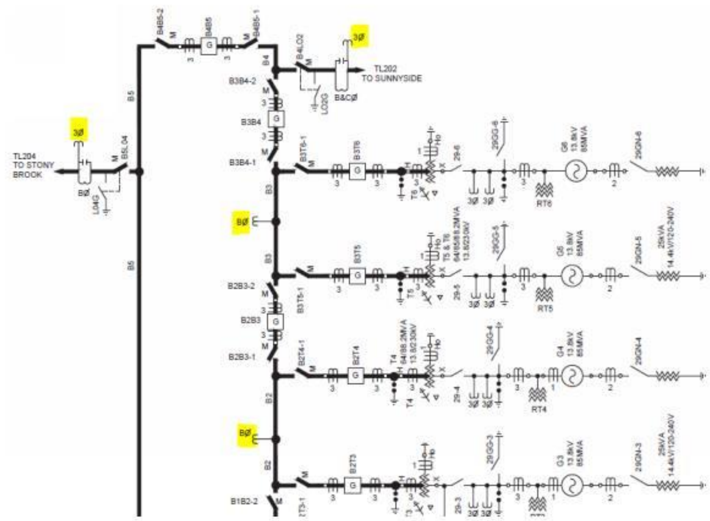


Figure 2-6: Location of CVTs on Different Buses

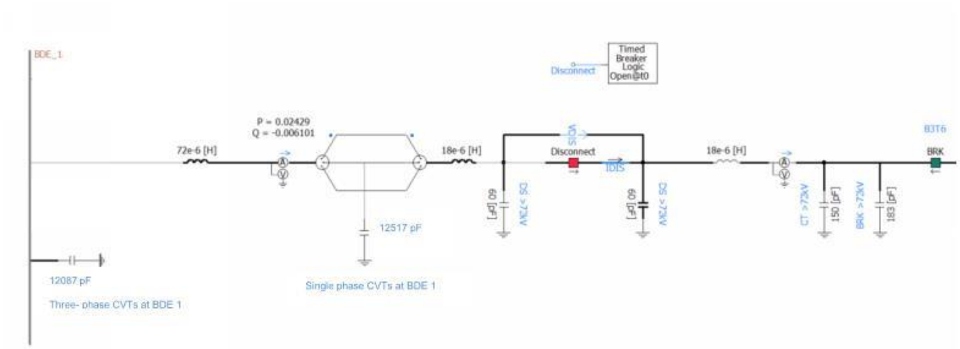


Figure 2-7: Approximate Equivalent Circuit of BDE TS#1 and TS#2

It should be noted that this is an approximate equivalent of the actual circuit and may not exactly match the real world phenomena. The magnitude of the transient voltage depends on many complex factors including the capacitance values and the maximum trapped charge in the capacitors during disconnect switch arcing.

Using the approximate equivalent circuit shown in Figure 2-7, the arcing of the disconnect switch during its opening operation is simulated, assuming that capacitors on phase C of the circuit are charged to their maximum voltage level (1.4 pu is assumed in this case) and the other two phases are charged to 50% (when one phase is at peak value, the other two phases are at 50% of their peak) of the maximum voltage level of phase C. These assumptions are made based on the fact that the fault events have happened on the C phase and also, based on the fault trace data, at the time the fault happened phase C was at its maximum magnitude, as seen in Figure 2-8.

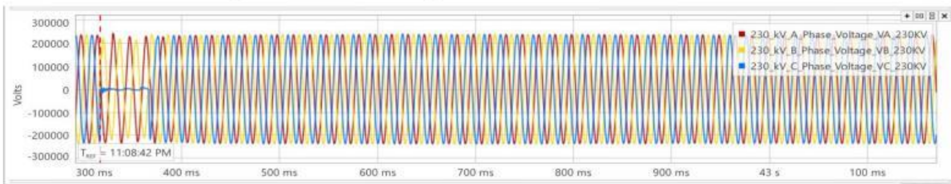


Figure 2-8: 230 kV-Bus Voltage

The capacitance values provided by NLH for the CVTs is used in developing the equivalent model, as listed in Appendix A. For the other components the values from IEEE Std 37.011 are used as listed in Table 2-1 and Table 2-2.

Table 2-1: Effective Capacitance of Inductive Instrument Transformer[2]

Maximum System Voltage (kV)	Outdoor Potential Transformers Capacitance (pF)	Outdoor Current Transformer Capacitance (pF)	SF_6 Insulated Potential Transformer for GIS Capacitance (pF)
15 to 72.5	125 to 500	75 to 260	200 to 400 (Epoxy insulated)
72.5 to 800	150 to 450	150 to 450	70 to 150 (Laminated foil, SF_6 insulated)

Table 2-2: Effective Capacitance of Capacitive Voltage Transformer

Voltage Class (kV)	Capacitance (pF)
145	4000 to 22000
170	4000 to 16500
242	3000 to 12500
362	2150 to 9500
550	1500 to 6300
800	2000 to 6200

[2] IEEE Std C37.011-1994, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

The simulation results show a transient voltage of up to almost 800 kV at the breaker terminals. This is an approximate value which depends on various parameters used in the simulation model. With more accurate data, a more realistic estimation can be obtained. The transient voltage at the breaker terminal and the current through the disconnect switch are shown in Figure 2-9 and Figure 2-10. The frequency of this transient voltage is in the order of 0.7 MHz.

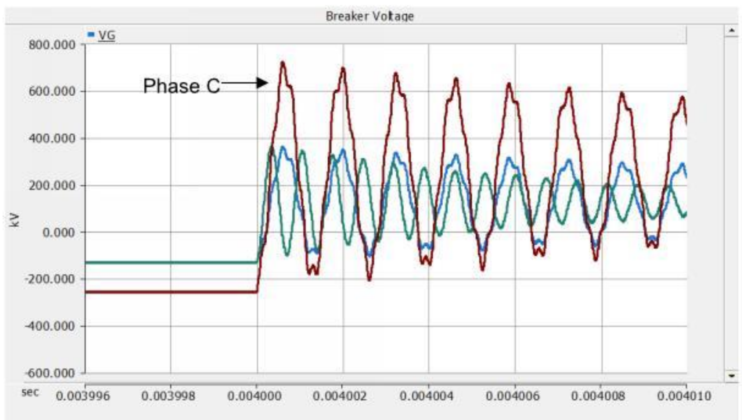


Figure 2-9: Transient Voltage at the Bus Side of the Breaker

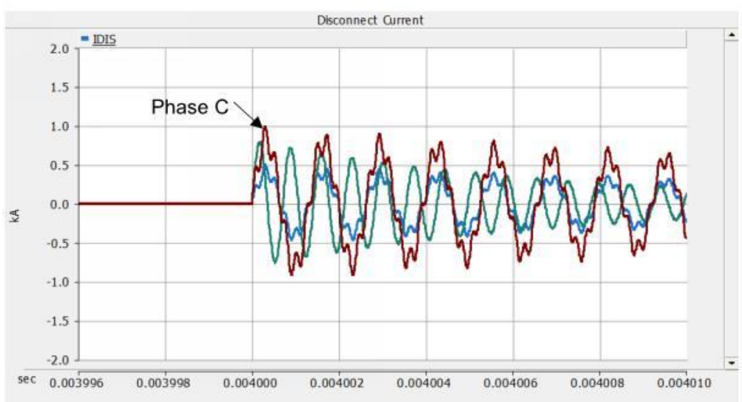


Figure 2-10: Transient Current through Disconnect Switch

For the fault that happened during disconnect operation, the breaker was open so the transients that were created in the system were mainly impacted by the components on the bus side of the breaker. For the other fault during breaker operation, the capacitances on the 13.8 kV side have minimal impact on the 230 kV side, due to presence of the transformer with a relatively big reactance (it becomes a very large impedance in high frequencies). The transients at the 230 kV side are mostly impacted by the capacitances at the 230 kV side. The results are hardly impacted by adding the capacitances at generator terminals.

2.4 Mitigation

Replacing bus CVTs with inductive (wound type) PTs has been considered one of the mitigation methods to minimize the transients due to capacitive effect. According to the values provided in IEEE Std 37.011 and as shown in Table 2-1 and Table 2-2, inductive PTs have considerably lower capacitance values compared to CVTs. In order to investigate the effect of inductive PTs, the capacitance values of CVTs in the PSCAD model were replaced by those of inductive type PTs. The results of PSCAD simulations show a reduction in voltage and current transient magnitudes on the bus side of the disconnect switch, thus showing the impact of the lower capacitance values.

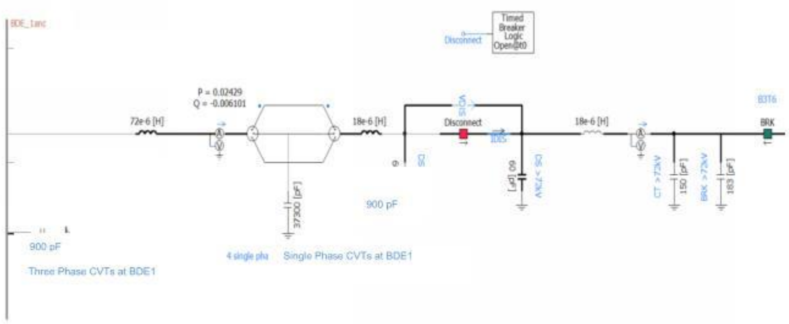


Figure 2-11: Capacitance Values after Replacing of CVTs with PTs

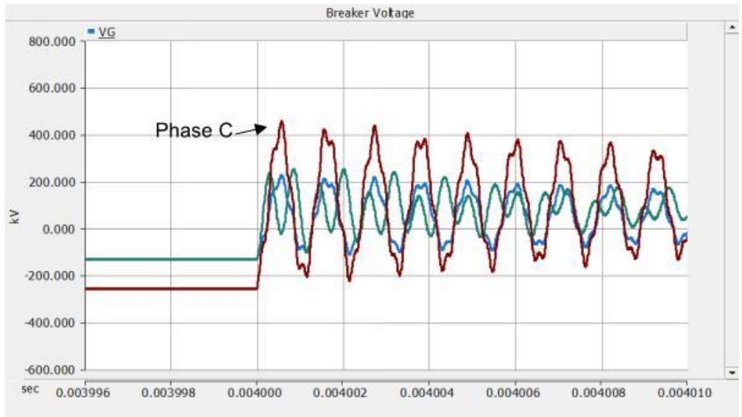


Figure 2-12: Transient Voltage at the Bus Side of the Breaker After Replacing CVTs With PTs

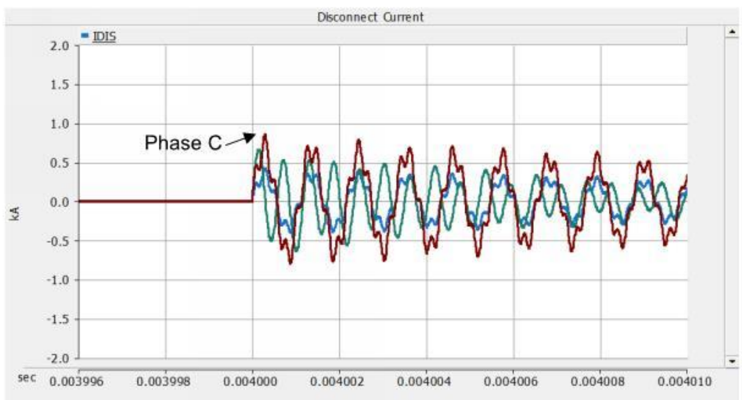


Figure 2-13: Transient Current through Disconnect Switch After Replacing CVTs With PTs

3. Opinion on the Breaker Type

Hatch reviewed the fault records provided and based on our analysis, it looks like the high voltage transients caused the breaker to flash-over. In saying this, as Hatch was not involved during the breaker investigation at the manufacturers facility, it is hard for us to provide a conclusive statement on the actual cause of the failure.

4. Conclusion

Decomposition of gas products as a result of arcing[3] during normal operation of SF6 breakers may lead to decreasing voltage withstand capability of breakers. Such gas products can increase the risk of breaker flashover under voltage transients created by switching actions. High frequency voltage and current transients can be observed during the operation of a disconnect switch where capacitive charges trapped in the circuit find their discharge path through switching arc and lead to voltage transients that might be higher than the withstand capability of the breakers.

This report investigates the breaker failure event that happened on 2019 Aug 24 in Bay D'Espoir TS#1 during the operation of the high side disconnect switch. Simulation of the system using an approximate equivalent showed a high voltage transient during opening of the disconnect switch. The high transient overvoltage is perceived to be caused by the high capacitance value of the CVTs installed on the system side of the disconnect switch. As a potential mitigation method, the possibility of replacing the CVTs with inductive PTs was investigated and the results of the simulation showed a significant reduction of transient overvoltage due to the lower capacitance values associated with inductive PTs.

[3] R. Sandoval, J.L. Eternod, "Evaluation of Methods for Breaker-Flashover Protection", 31st Annual Western Protective Relay Conference, October 2004.

Appendix A

BDE 230 kV CVTs Capacitance Values

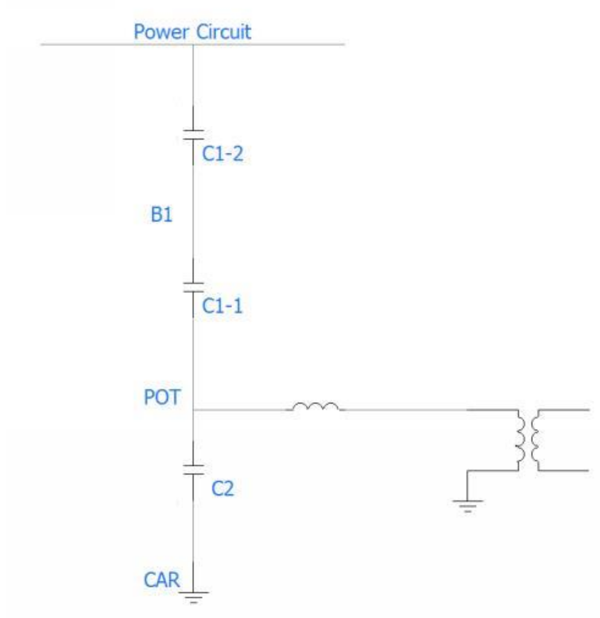


Figure 4-1: A Simplified Schematic of the CVT for the Capacitance Values Provided in Table Below

HATCH

Newfoundland and Labrador Hydro (NLH)
Bay D'Espoir Terminal Station#1
H361486

Engineering Report
Engineering Management
Breaker Failure Study

BDE 230 kV CVTs Capacitance Values

Station	Location	Phase	C2 (CAR-POT)	C1-1 (B1-POT)	C2 ser C1-1	C1-2 (B2-B1)	Overall Calc. L - Gnd	%PF
TS1	B1	B	71500	14856	12300	12200	6124.90	0.07
TS1	B2	B	179250	13667	12699	12773	6367.95	0.07
TS1	B3	B	71000	14877	12300	12300	6150.00	0.06-0.07
TS1	TL202	A	91100	17956.6	15000	14900	7474.92	0.24-0.25
TS1		B	91100	17956.6	15000	14600	7398.65	0.25
TS1		C	76403	15298.1	12746	12810	6388.96	0.06
TS1	TL204	A	59800	12008	10000	10000	5000.00	0.06
TS1		B	58900	12045	10000	10000	5000.00	0.06
TS1		C	60100	12140.2	10100	10100	5050.00	0.06
TS1	B10 (ts1)	B	154766	13472.9	12394	12500	6223.39	0.05
TS2	B10 (ts2)	B	73600	15057.3	12500	12600	6274.90	0.07
TS2	B9	A	73700	15053	12500	12400	6224.90	0.07
TS2		B	72800	15091	12500	12400	6224.90	0.07
TS2		C	72700	15095	12500	12600	6274.90	
TS2	B11	B	74400	15024	12500	*12500*	6250.00	0.06
TS2	TL231	*A*	83723	15419.043	13021	13012	6508.25	0.06
TS2		*B*	83723	15419.043	13021	13012	6508.25	
TS2		*C*	82474	15606.21	13123	13095	6554.49	
TS2	TL267	A	81563	15549.871	13060	13050	6527.50	
TS2		B	83091	15570.212	13113	13072	6546.23	
TS2		C	81824	15380.683	12947	12889	6458.97	
TS2	TL234	A	74100	15036	12500	12400	6224.90	0.07
TS2		B	169506	13595	12586	12691	6319.14	0.05
TS2		C	72900	15087	12500	12500	6250.00	0.07
TS2	TL206	A	73500	?	12500	12500	6250.00	0.07
TS2		B	73700	?	12600	12500	6274.90	0.07
TS2		C	73900	?	12500	12500	6250.00	0.07
TS2	B7	A	82902	15586.745	13120	12992	6527.84	
TS2		B	82801	15576.202	13110	13148	6564.49	
TS2		C	83058	15592.572	13128	13097	6556.24	

Appendix B

Bay d’Espoir Terminal Station 1 System Operating Diagram

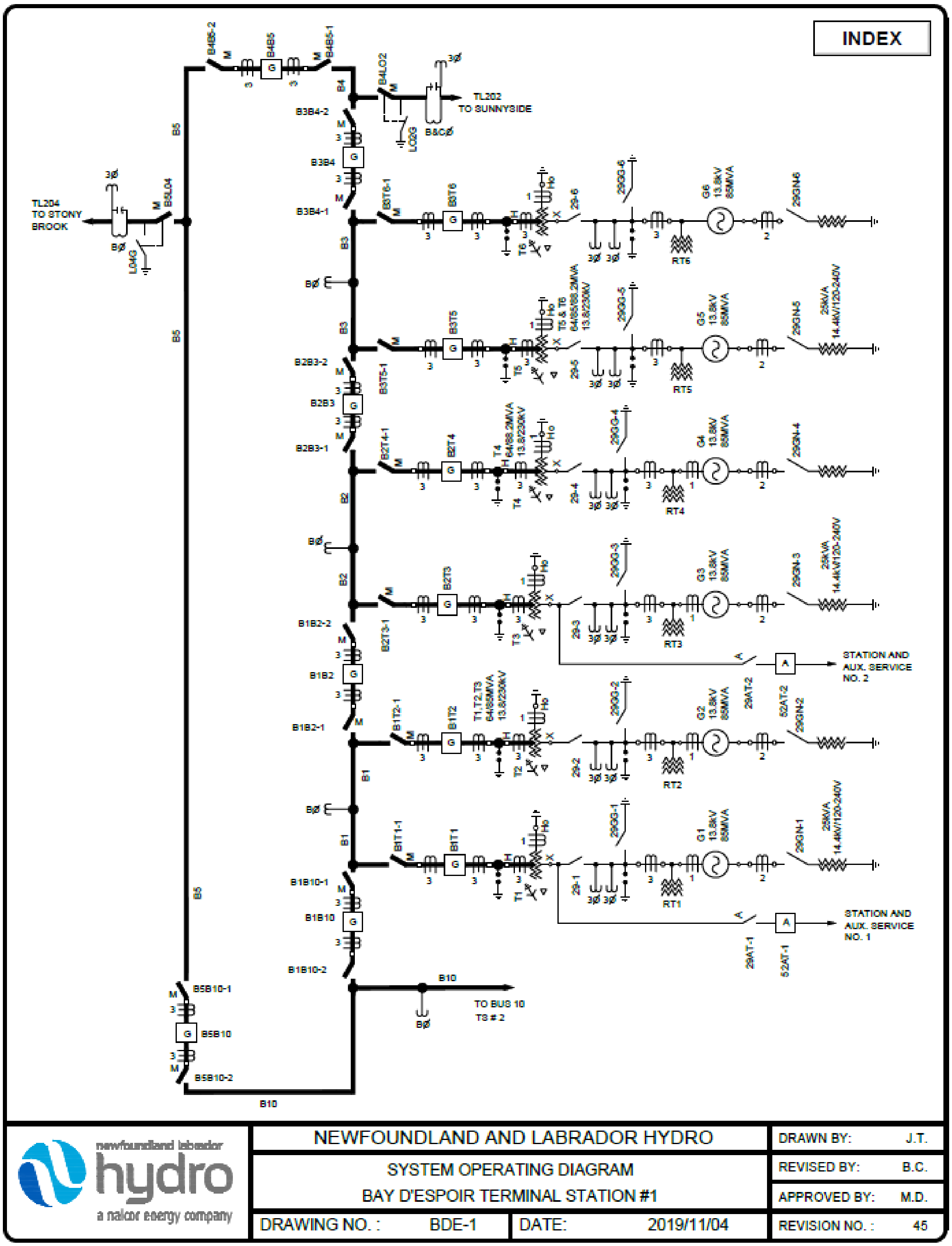


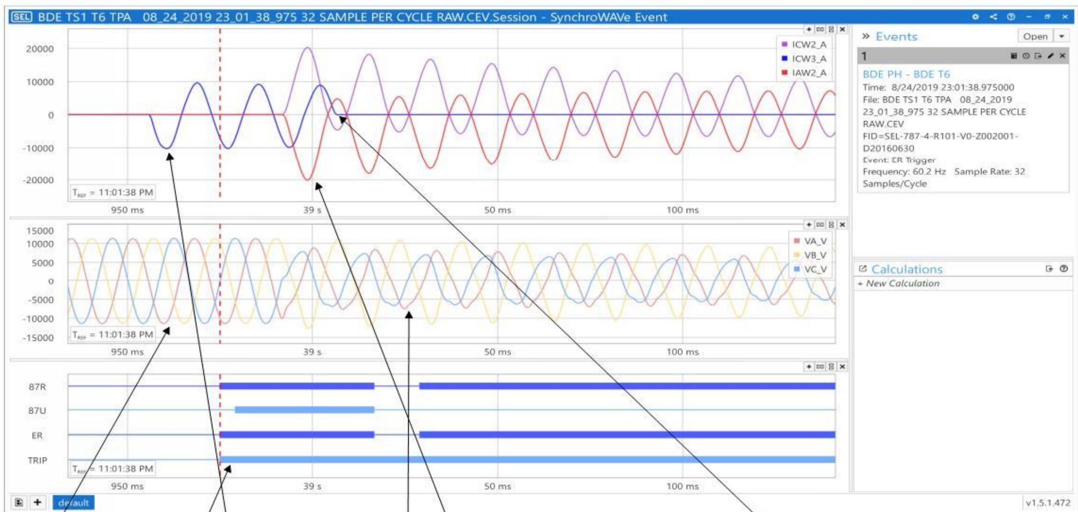
Figure 1: Bay d'Espare Terminal Station 1 System Operating Diagram

Appendix C

Bay d'Espoir B3T6 Failure Relay and Digital Fault Recorder Records

newfoundland labrador hydro
a nalcor energy company

TRIP VIEWED FROM TRANSFORMER T6 PROTECTION RELAY



No effect to generator voltage until current starts to flow on low side.

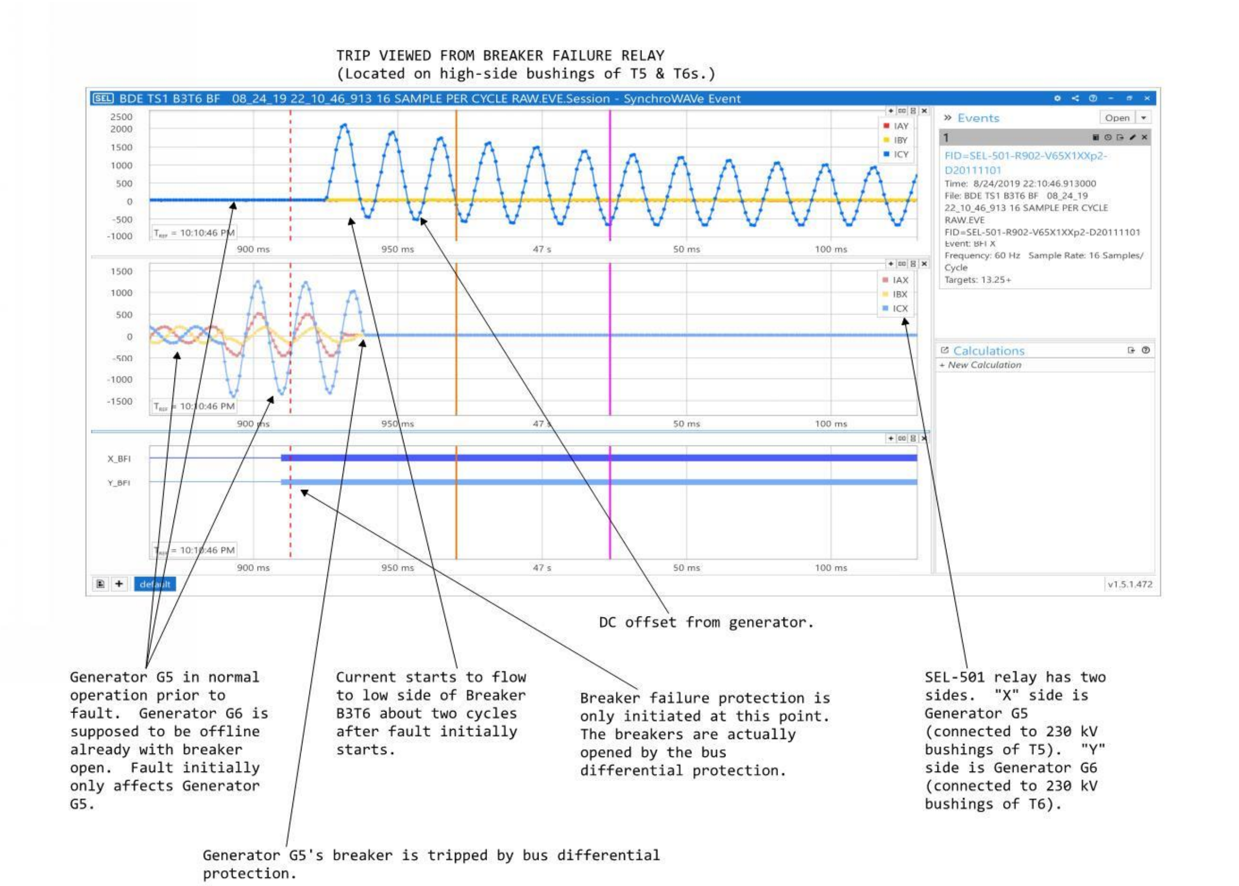
Initial contribution to fault seen from Phase C bushing on bus side of Breaker B3T6.

Current starts to flow through Transformer T6 and Generator G6 to supposedly open Breaker B3T6. Seen as matched pair of waveforms on 13.8 kV side of delta-wye Transformer T6. (Delta-wye transformer makes line-to-ground fault look like phase-to-phase fault.)

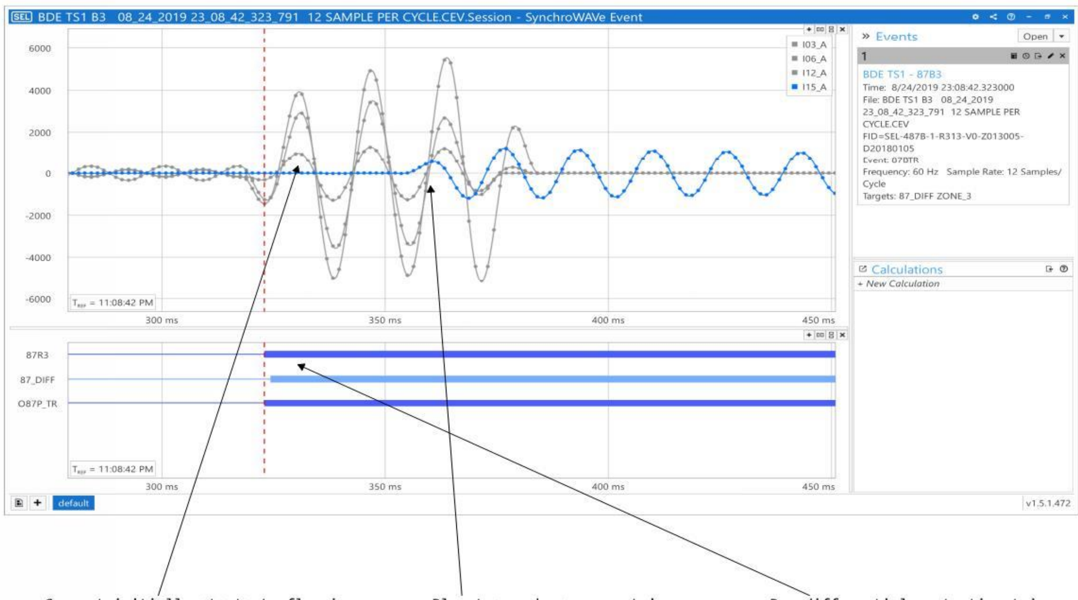
Fault contribution through high side Phase C bushing on Breaker B3T6 ceases when other breakers on Bus B3 open. This is the result of the bus differential protection operation; the breaker failure relay trips approx. a0.2 seconds later.

Transformer T6 trips at this point, due to initial fault contribution. This implies that the (initial) fault is between the high-side bushings of Breaker B3T6 and the CTs on the 13.8 kV side of the transformer.

Voltage somewhat reduced on low side due to fault. Voltage on high side is almost zero (not shown). This implies both faults are at 230 kV level.


TRIP VIEWED FROM BREAKER FAILURE RELAY
(Located on high-side bushings of T5 & T6s.)
BDE TS1 B3T6 BF 08_24_19 22_10_46_913 16 SAMPLE PER CYCLE RAW.EVE.Session - SynchroWAVe Event
IAY
IBY
ICY
IAX
IBX
ICX
X_BFI
Y_BFI
900 ms
950 ms
47 s
50 ms
100 ms
Events
Calculations
+ New Calculation
DC offset from generator.
Generator G5 in normal operation prior to fault. Generator G6 is supposed to be offline already with breaker open. Fault initially only affects Generator G5.
Current starts to flow to low side of Breaker B3T6 about two cycles after fault initially starts.
Breaker failure protection is only initiated at this point. The breakers are actually opened by the bus differential protection.
SEL-501 relay has two sides. "X" side is Generator G5 (connected to 230 kV bushings of T5). "Y" side is Generator G6 (connected to 230 kV bushings of T6).
Generator G5's breaker is tripped by bus differential protection.

TRIP VIEWED FROM BUS DIFFERENTIAL RELAY
(CT's located in 230 kV bushings.)

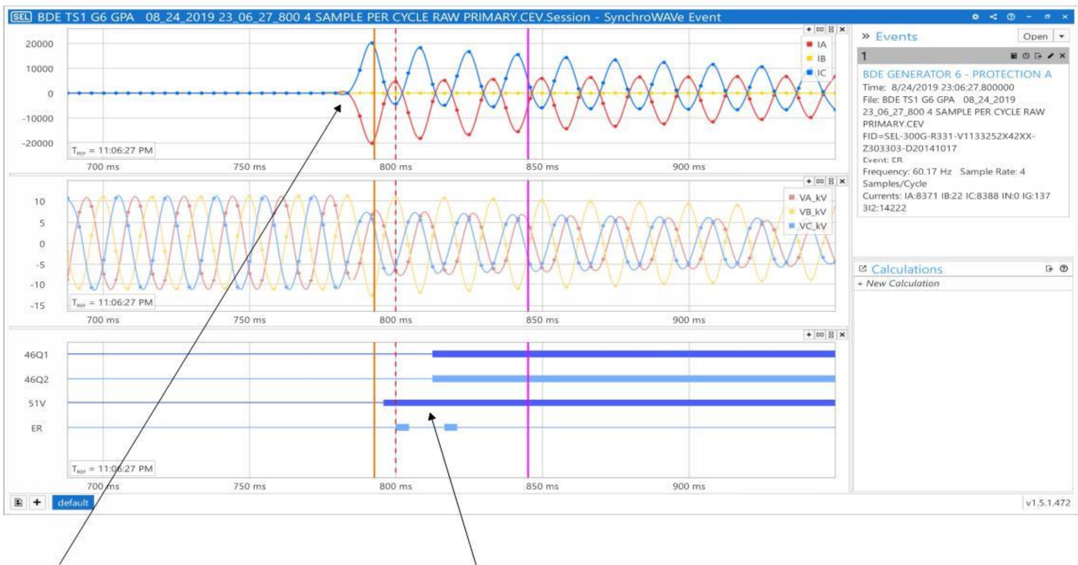


Current initially starts to flow in Phase C of Breakers B3T5, B2B3, and B3B4. No current for two cycles in Breaker B3T6 (supposed to be open).

Blue trace shows current in Phase C generator-side bushing of Breaker B3T6 two cycles after fault starts. Note that this is measured on load-side bushings of Breaker B3T6, showing that the issue is in the breaker.

Bus differential protection trips.

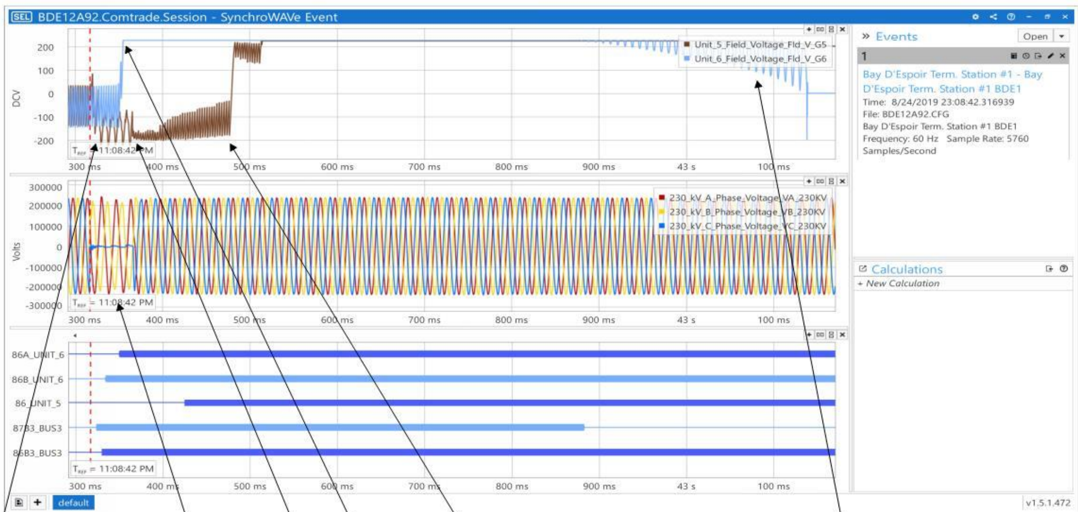
TRIP VIEWED FROM GENERATOR G6 RELAY



Current only starts two cycles after the 230 kV-level fault begins.

46 and 51V protections provide sensitive, time-delayed protection for unbalance and overcurrent, respectively. This appears to indicate that Breaker B3T6 was open and that the fault initially only affected the 230 kV side. If Phase C of B3T6 had jammed, I would have expected the 46 element (negative sequence/unbalance) to already be picked up at this point.

TRIP VIEWED FROM DFR
(Only has field voltages from generators.)



Fault initially affects only Generator G5, which tries to support voltage. Generator G6's breaker is open.

Note the voltage collapse on 230 kV bus. This shows that the fault is on the 230 kV side of the transformer.

Breaker failure operation. Breakers are already open, so it just trips Generator G5's exciter.

Current on generator side of Breaker B3T6 starts.

Bus differential protection opens breaker, but does not trip generator. Generator G5 would have gone to speed-no-load had it not been tripped by breaker failure protection 0.2 s later.

Oscillation in Generator G6 field voltage probably due to unbalanced fault.

Appendix D

Installed General DT1–245P F3 Circuit Breakers

Table 1: Installed General Electric DT1–245P F3 Circuit Breakers

Terminal Station	Circuit Breaker Name	Application	Purchase Year	Installation Year	Failure Year
BDE	BDE B1T1	Generator	2015	2016	-
BDE	BDE B2T3	Generator	2015	2016	-
BDE	BDE B2T4	Generator	2019	2019	2019
BDE	BDE B3T5	Generator	2018	2019	2019
BDE	BDE B3T6	Generator	2019	2019	2019
BDE	BDE B1B2	Bus	2015	2016	-
BDE	BDE B2B3	Bus	2018	2018	2018
BDE	BDE B3B4	Bus	2017	2018	-
BDE	BDE B5B10	Bus	2016	2018	
BDE	BDE B1B10	Bus	2018	2019	-
BDE	BDE B7L06	Line/Bus	2016	2017	-
BDE	BDE B7L67	Line/Bus	2016	2017	-
BDE	BDE B9L31	Line/Bus	2016	2017	-
BDE	BDE L31L67	Line/Bus	2016	2017	-
Buchans	BUC L32L33	Line/Bus	2017	2017	-
Hardwoods	HWD B1L66	Line	2015	2015	-
Massey Drive	MDR B5L11	Line	2017	2017	-
Massey Drive	MDR B1L28	Line	2017	2018	-
Oxen Pond	OPD B1L36	Line	2016	2016	-
Stony Brook	STB B2L04	Line/Bus	2017	2018	-
Stony Brook	STB B1L32	Line/Bus	2019	2019	-
Sunnyside	SSD L02L07	Line/Bus	2016	2016	-
Upper Salmon	USL L63T1	Line/Bus	2017	2017	-
Western Avalon	WAV B1L37	Line/Bus	2017	2018	-
Western Avalon	WAV L03L17	Line/Bus	2019	2019	-
Western Avalon	WAV L01L03	Line/Bus	2018	2019	-
Western Avalon	WAV B1B3	Bus	2018	2019	-