Catastrophic Breaker Failures Due to Missing Current Zero-Crossings in Highly Shunt-Compensated 500 kV Lines—Point-on-Wave, Reclosing, and Protection Considerations

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Presented at the
50th Annual Western Protective Relay Conference
Spokane, Washington
October 10–12, 2023

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***Abstract*—BC Hydro has experienced five catastrophic failures of relatively new 500 kV sulfur hexafluoride (SF_6) breakers on transmission lines since 2012. These failures occurred on lines equipped with shunt reactors, which compensate for over 50 percent of the line charging current. The root cause of these failures was missing zero-crossings in the line current during protection trips that were preceded by line energizations. The energizations were either point-on-wave (POW)-controlled or uncontrolled. Modern SF_6 breakers are highly susceptible to failure when zero-crossings in the interrupting current are missing. This paper discusses catastrophic failures and explores options to prevent similar incidents. While one failure occurred after manual line energization, the other four failures were after an autoreclose, which prompted a review of the autoreclose supervision logic. The paper proposes incremental improvements in the autoreclose supervision logic as countermeasures and advocates for a significant shift in the POW-controlled switching philosophy.**

I. Introduction

Air-blast circuit breakers with pre-insertion resistors have been used since the first BC Hydro 500 kV system was installed in the late 1960s. Pre-insertion resistors are typically about 400 Ω and are inserted momentarily into the extra-high-voltage (EHV) circuit during circuit breaker operations. Their momentary insertion simultaneously reduces both voltage and current switching transients. While BC Hydro and utilities worldwide have had good operational experience, circuit breakers with pre-insertion resistors are perceived as expensive to purchase. The mechanical complexity of inserting the resistor mechanism requires periodic maintenance to avoid malfunction [1].

In 1994, BC Hydro collaborated with a leading EHV station equipment supplier and deployed its first point-on-wave (POW) technology application to limit switching voltage transients. The innovation had two intended benefits [2] [3]. The first benefit was that the application of POW technology permitted a compact 500 kV line design with a smaller transmission footprint and lower cost due to the reduced switching voltage transients. The second benefit was that circuit breakers without pre-insertion resistors could be used, thus reducing costs. Based on positive operational experience over 5 years after the first installation, BC Hydro decided to expand the application of POW technology during an EHV breaker replacement program spanning the next 10 years. Almost the entire fleet of aging air-blast breakers with pre-insertion resistors was replaced with modern sulfur hexafluoride (SF_6) and mixed gas breakers (simply referred to as SF_6 circuit breakers) equipped with POW control. Although pre-insertion resistors were previously installed on all breakers at both line terminals and allowed energization from either terminal, POW controls are provided only at one line terminal, limiting controlled line energization to one terminal.[1] As a result, the line cannot be energized from the other terminal due to the lack of controlled switching capability. The line autoreclose is also designed with lead and follow terminal logic, in which only the line breakers with POW control are assigned as the lead (or first) terminal to close. The line energization from the follow terminal due to an incorrect autoreclose operation, leading to uncontrolled line energization, is not desirable.

BC Hydro experienced its first breaker failure in 2012, leading to the realization of certain limitations of applying POW control. Subsequently, four more failures occurred. All failures happened on highly shunt-compensated lines[2] where protection tripped during a manual energization or an autoreclose. Recorded waveforms of the line energization currents confirmed that missing zero-crossings during the trip were the root cause of the failures. The SF_6 circuit breakers failed while attempting to interrupt the line current without zero-crossings for several cycles. This paper intends to share lessons learned from failures with peer utilities and present corrective actions, either applied or planned.

The remainder of this paper is structured into five sections. Section II focuses on the considerations of POW applications

[1] Once the line is successfully energized from the lead terminal, no transient overvoltage control is necessary to close the breaker at the follow terminal because the voltage across this breaker is expected to be small, assuming that the parallel transmission lines are maintaining the path synchronism.

[2] Shunt reactors are connected to the line and sized to compensate more than 50 percent of the line's positive-sequence capacitance.

on highly shunt-compensated lines. The primary objectives of POW-controlled energization were to minimize voltage transients during line switching and reduce the probability of conductor-to-ground flashover, particularly upon line autoreclose. However, in highly shunt-compensated lines, minimizing voltage transient during manual energization or suboptimal POW performance during autoreclose leads to missing current zero-crossings, which poses a potential breaker failure risk if a protection trip occurs during line energization.

Section III provides a comprehensive description of the failure events encountered. The section analyzes the specific incidents and their associated waveforms, highlighting missing zero-crossings during line energization and explaining protection trips and the resultant breaker failures.

Section IV summarizes all contributing factors to the failures, identifies common elements, and presents the lessons learned. Section V focuses on a roadmap of corrective actions that have been or will be implemented. Incremental improvements in protection measures were applied after each failure event. However, since the failures persisted, new corrective actions were explored. These actions include a significant change in BC Hydro's philosophy of POW-controlled switching to prevent missing zero-crossings in the line energization currents. Considering that four failures involved incorrect autoreclose, a discussion on improving autoreclose is included to minimize the probability of similar failures at the follow terminals. Additionally, as a long-term corrective measure, the proposal suggests reintroducing pre-insertion resistors in highly shunt-compensated lines.

Lastly, Section VI summarizes the lessons learned and conclusions from failure investigations. It emphasizes the importance of proactive measures to prevent similar incidents. It highlights the need to share these lessons to enhance EHV transmission systems' overall reliability and safety.

II. POW-Controlled Switching

Uncontrolled energization of EHV transmission lines can produce high switching voltage transients that can cause conductor-to-tower flashovers. Therefore, it is necessary to have means to limit the switching transients below the flashover voltage, referred to as air gap critical flashover (CFO) levels, during manual and automatic line energizations. This section uses a lumped parameter model of the transmission line to illustrate the risk of switching transients that exceed CFO, discusses methods to limit them, and highlights the predicament of using innovative POW technology to restrict them in highly shunt-compensated lines.

A. Switching Surges

Fig. 1 shows a transmission line with its inherent shunt capacitance distributed along the entire line length and its simplified lumped representation. The highly capacitive nature prevents the line voltage from changing instantaneously upon its energization.

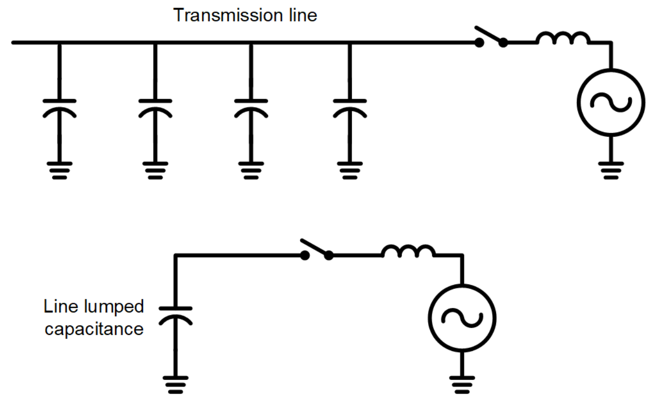

Fig. 1. EHV line with an inherently distributed capacitor and its lumped representation.

A switching transient with both high-frequency and high-voltage magnitudes (referred to as switching surge voltage) is produced during the line's transition from a de-energized (or partially energized from the trapped charge) to an energized state. Using the simplified model, the switching surge can be expressed in the form of the following equation when a capacitor is energized by a 60 Hz voltage source with a small inductive source impedance.

$$Vc(t)_{t>0+} = VS(t=0)\left(1-\cos(2\pi fr \cdot t)\right) + Vc(t=0)\cdot\cos(2\pi fr \cdot t) \quad (1)$$

where:

$Vc(t)_{t>0+}$ is the switching surge voltage immediately after line energization.

VS(t = 0) is the source voltage at the instant of energization.

Vc(t = 0) is the capacitor voltage from the trapped charge at the moment of energization.

fr is the resonant frequency of the series LC network formed by the equivalent inductance and the line capacitance.

The fr is several orders of magnitude greater than 60 Hz. Fig. 2 illustrates that the crest of the capacitive voltage transient can reach as high as 3 pu immediately after switching, assuming the source voltage at the positive peak is 1 pu (i.e., VS(t = 0) = +1 pu) and the capacitor voltage at the negative peak is –1 pu (i.e., Vc(t = 0) = –1 pu). The crest can exceed 3 pu when energizing the capacitive line shortly after de-energization, as in high-speed autoreclosing applications [4] [5]. In a well-designed system in which circuit breakers are not subjected to multiple restrikes or the strong source energizes the line, the switching transient voltages rarely exceed 3 pu and typically not even 2.5 pu.

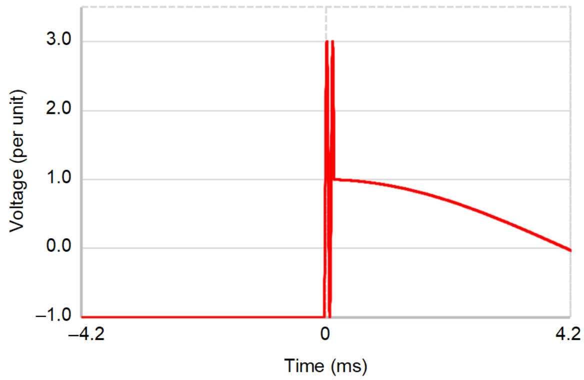

Fig. 2. Switching transients approaching 3 pu in the capacitive network.

EHV lines are typically equipped with high-speed autoreclose[3] after trips from the line protection system to maintain system stability. Fig. 3 illustrates high-frequency voltage transients at the open terminal of a 500 kV line after an autoreclose. The autoreclose was simulated on an electromagnetic transients program using the detailed distributed parameters of a 110 km line. The line has capacitively coupled voltage transformers (CCVTs), which, unlike magnetic voltage transformers (VTs), slow down the discharging of electric charge retained by the line capacitance after the trip.[4] The crest of the voltage transient exceeded 230 percent of the applied voltage. Higher crests can be anticipated for longer lines. The line surge arresters were intentionally disconnected from the model to illustrate the risk of high voltage transients without voltage control.

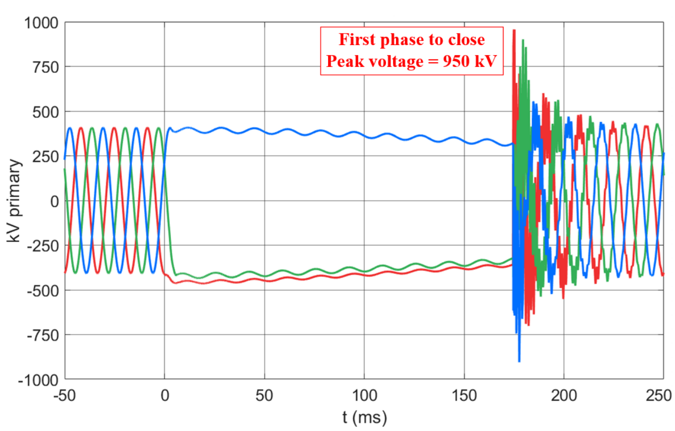

Fig. 3. Switching surges during autoreclose of an uncompensated 500 kV line.

B. *Switching Surge Control on Transmission Lines*

BC Hydro has two 500 kV line constructions: the original lines built in the 1960s and the newer lines built with compact line construction. The original lines are insulated to have an air gap CFO of 1,120 kV or about 2 pu with 550 kV, the maximum operating voltage, as the reference. Hence, the original line construction is called the 2 pu line. The newer lines with compact construction are insulated to have a CFO of 900 kV or about 1.7 pu, referred to as the 1.7 pu lines.

Surge voltages after line energization, mainly via autoreclose, can have crest values exceeding 2.0 pu. Controlling transient voltages and limiting them within the design levels are necessary to prevent flashovers during line energizations. However, the crests of transient voltage depend on many factors and are statistical in nature. Usually, transmission line design and energization methodology are selected to keep 98 percent of transient voltage under CFO [6]. As a result, BC Hydro's control methodology ensures that the maximum switching surge voltage is under 2.0 pu for the original lines and 1.7 pu for the newer lines, with a 98 percent probability.

Fig. 4a shows a circuit diagram of the pre-insertion resistor method of controlling voltage transients. The circuit breaker control system inserts a large power resistor in a single step or multiple steps and controls the insertion duration to reduce switching surges [7] [8]. The power resistor is then shunted shortly after line energization. The resistor value is selected to match the line surge impedance loading, which is typically about 400 Ω for the 500 kV lines, and its insertion duration generally is in the order of 8 to 16 milliseconds [8]. BC Hydro and utilities around the world historically used air-blast circuit breakers that came with single- or multistep pre-insertion resistors. While the design goals of limiting voltage transients due to switching were generally attained by using resistor combinations and insertion durations, the mechanical complexity of the control system required periodic maintenance and outages to carry out maintenance. The mechanical malfunctions contributed to reduced breaker reliability.

Fig. 4b shows a circuit diagram of a modern POW-controlled switching methodology to control voltage transients due to switching. It relies upon a precise closing time to achieve a smooth transition of the line from a de-energized or partially energized state during the autoreclose dead time state to an energized state. For de-energized transmission lines, zero voltage across the breaker at closing eliminates voltage transients due to switching.

[3] High-speed autoreclose is defined as autoreclose within 1 second of the line tripping.

[4] Note that the simulated waveforms, as shown, are primary line voltages and are not the CCVT secondary outputs. CCVT outputs are tuned to power frequency (60 Hz) and do not exactly replicate the trapped charge on the line.

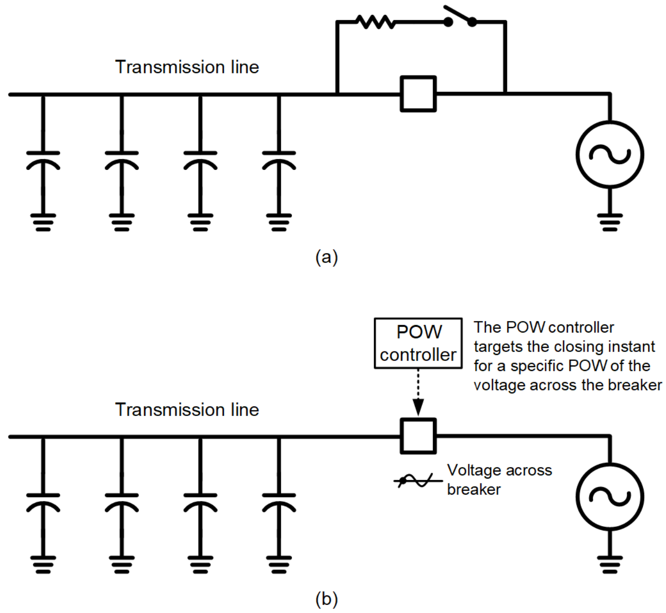

Fig. 4. Control of switching transients in an EHV line using (a) a pre-insertion resistor and (b) POW-controlled closing.

BC Hydro implemented their first application of POW-controlled switching devices in the mid-1990s, together with metal-oxide surge arresters, on a 1.7 pu transmission line. These surge arresters provided additional control to account for the deviation between the theoretical target closing instant and the actual closing instant. This deviation can occur due to the control algorithm's inability to precisely estimate the target closing instant in real time, errors in the CCVT output, or drift in the breaker's closing time [9]. In a 60 Hz system, a 4-millisecond (approximately a quarter-cycle in a 60 Hz system) error between the theoretical and actual closing time significantly impacts the performance of the controlled switching system, from the optimal closing time to the least desirable closing time. Three high-energy metal-oxide surge arresters were used, with two per phase positioned at each line terminal and one per phase in the midline position to improve transmission system insulation performance and reduce stress on station equipment [2] [3]. These surge arresters had a protective level of 1.5 pu, lower than the standard 500 kV line surge arresters' protective level of 1.8 pu. The high-energy surge arresters were appropriately sized to handle the contingency of POW failure. The SF_6 circuit breakers used in the system were selected to have a spring-hydraulic mechanism and have demonstrated minimal variation in closing time [9].

C. *Controlled Closing on Highly Shunt-Compensated Line*

After 5 years of experience without incident since the first deployment of POW-controlled closing, BC Hydro replaced nearly all aging 500 kV air-blast breakers equipped with pre-insertion resistors with new SF_6 breakers equipped with POW controllers. Five of these breakers have failed catastrophically since 2012, and all were on highly shunt-compensated lines. The protection tripped during the line energizations, and breakers failed while attempting to interrupt line currents with missing zero-crossings.

The challenge of applying POW technology to a highly shunt-compensated transmission line is depicted using Fig. 5, which illustrates a shunt-compensated line and its simplified lumped parameter representation. For simplicity, resistive elements in the network are disregarded. The shunt reactor compensates for 70 percent of the line capacitance in this illustration. During steady-state operation, the shunt reactor supplies 70 percent of the charging line current, while the remaining 30 percent comes from the source. Both the line and the reactor are energized and de-energized simultaneously.

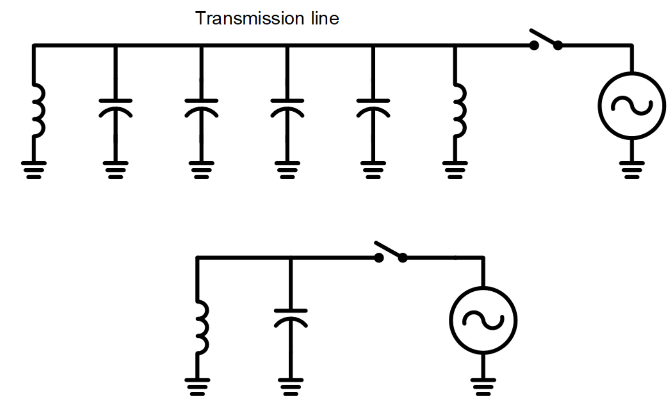

Fig. 5. A shunt-compensated line and its lumped representation.

1) *POW Conundrum During Manual Line Energization*

To minimize voltage transients due to switching, the line's overall capacitive characteristics require energization when the voltage difference between the source and the line is zero. This occurs at a voltage zero for a de-energized line, after any trapped charges have had enough time to dissipate (e.g., during manual energization). As the reactor is part of the line circuit, it also gets energized at a voltage zero along with the line. The line shunt reactor is typically an air-gapped iron-core or a full air-core reactor that retains a small residual flux, which can be neglected. Upon energization at a voltage zero, this reactor draws rated current with a full direct current (dc) offset because current through a reactor cannot change instantaneously.

Fig. 6a demonstrates a smooth transition, without voltage transients, from a de-energized to an energized state after the 70 percent shunt-compensated line is energized at a voltage zero. Fig. 6b shows that the line current, which is the sum of the capacitive charging current and the shunt reactor current (referred to as compensated line charging current), has no zero-crossings. This lack of zero-crossings is due to a higher dc (70 percent of the line's capacitive charging current) than alternating current (ac) (30 percent). This principle applies if the shunt compensation in the line is more than 50 percent, which makes the line a highly shunt-compensated line. As a result, POW-controlled closing, designed to minimize switching overvoltage transients, unintentionally leads to missing zero-crossings in a highly shunt-compensated line current.

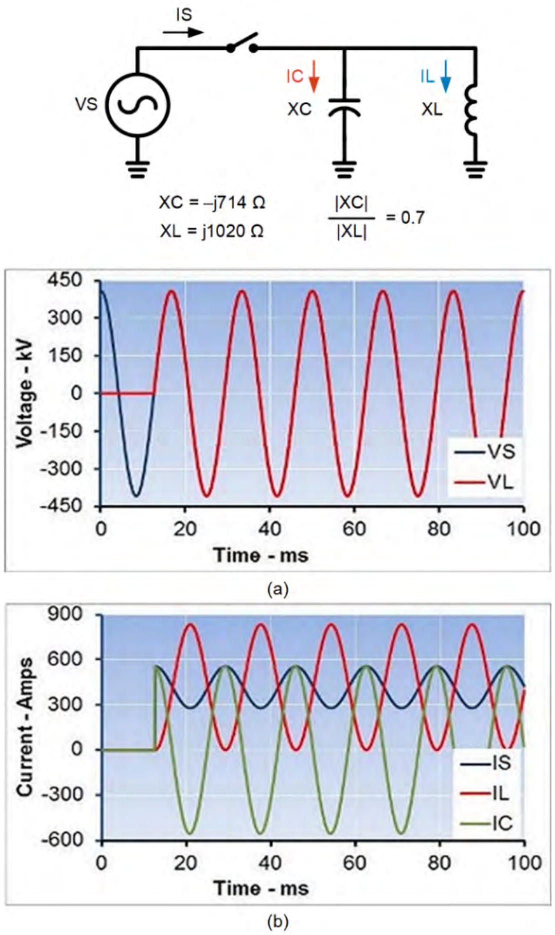

Fig. 6. Switching (a) voltage and (b) current in a 70 percent compensated line with target closing at voltage zero across the breaker.

It is important to note that modern SF_6 circuit breakers can fail even when interrupting low-magnitude currents [10] (as low as 10 A) with missing zero-crossings. If a protective trip is issued immediately after closing the breaker from POW control, it is likely to cause SF_6 circuit breaker failures. In summary, applying POW-controlled switching during manual energization of a highly shunt-compensated line presents competing requirements. On one hand, controlled closing at a voltage zero minimizes voltage transient but maximizes dc offset in the current, which introduces missing zero-crossings and poses a risk of breaker failure. On the other hand, the POW-controlled closing at maximum voltage minimizes dc offset in the current but maximizes voltage transient, risking line conductor flashover or even damage to the station equipment due to stressed insulation.

2) POW Challenge During Autoreclose

In contrast to uncompensated lines, a compensated line with a shunt reactor offers a discharge path for the trapped charge after the line opens at both terminals. During autoreclose, the electrical energy from the trapped charge oscillates between the line capacitance and the inductance of the shunt reactor. The open line voltage during autoreclose is known as the ringdown voltage, which oscillates at subsynchronous frequency when the shunt compensation is less than 100 percent.

For example, in a 70 percent shunt-compensated line with a 60 Hz source frequency, the ringdown voltage frequency is approximately 50 Hz, calculated as:

$$f_{\text{ringdown}} = \sqrt{0.70} \bullet 60 \text{ Hz} \quad (2)$$

Fig. 7 illustrates the source voltage (VS) at a power frequency of 60 Hz, the line ringdown voltage (VL) at approximately 50 Hz, the voltage across the closing breaker (V_{BKR}), which is the difference between the source and line ringdown voltages (VS – VL), and the line reactor current (IL) during the autoreclose. V_{BKR} exhibits a beat-frequency pattern, with the beat minimum representing the desired closing target corresponding to the minimum voltage across the breaker. The beat frequency is 10 Hz, which is the difference between the source and ringdown voltage frequencies. In Fig. 7, the source voltage (VS) is also zero at the beat minimum, representing the desired closing target to avoid switching voltage transients. Unlike manual energization, in which the reactor current was zero before energization, the reactor current (IL) is at the negative peak. It lags 90 degrees behind the source voltage (VS) at the desired closing target, allowing reactor re-energization together with the line without dc offset current during autoreclose. The correct phase relationship between the reactor voltage and current at the beat minimum is introduced by the line ringdown voltage, forcing the current into the reactor during the three-phase open interval.

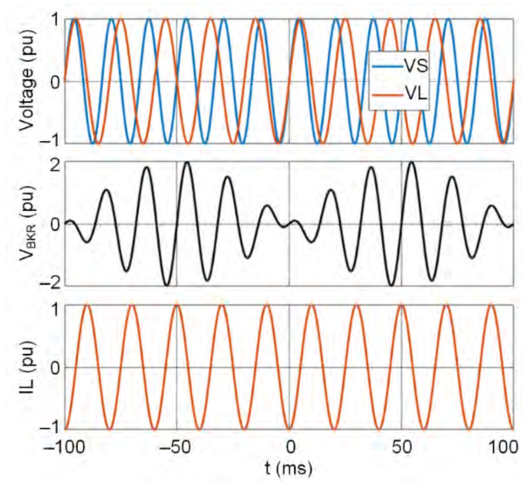

Fig. 7. The source voltage (VS), line ringdown voltage (VL), voltage across the closing breaker (V_{BKR}), and reactor current (IL) during a three-phase open time interval.

The high-speed autoreclose at the beat minimum appears to mitigate the conundrum by offering a closing instant that minimizes voltage transients and avoids missed current zero-crossings. But determining the beat minimum in a three-phase system is challenging. First, it occurs at the slip frequency between the source and ringdown voltages. High compensation lowers the slip frequency, which increases the duration between the beat minimums and reduces the opportunity to detect them within the available short time duration to close the breaker upon the expiration of the three-phase open time interval. Second, the POW controller must anticipate the beat minimums in all three phases to account for the breaker closing time and send individual close commands to each phase at different instants.[5] The beat patterns on the unclosed phases begin to change after the first phase closes due to variations in the interphase mutual couplings among the line conductors and the resonant conditions from the single-phase (or two-phase) energized line.

Modern POW controllers use sophisticated algorithms to anticipate the beat minimums. However, they can still fail to detect them, or beat minimums may not exist within the available short duration to close all three phases at the end of a three-phase open interval. Thus, a POW controller typically switches to backup mode if it cannot identify the beat minimum within a settable delay[6] for the next phase close after closing the first or second phase. In backup mode, the remaining open phases are closed after a fixed delay, either simultaneously or staggered, depending on the controller design. The aim is to minimize the duration of the overall three-phase open condition[7] for stability purposes and to prevent a line from remaining energized on only one or two phases for an extended time. In backup mode, the closing is not designed to minimize either the switching surge voltage or the dc offset current in the reactor. While three surge arresters on the line look after line insulation performance and protect station equipment from surge voltages, as discussed in Section II.B, there is no control of the dc offset current.

The difficulty of the POW-controlled autoreclose at the lead terminal of a highly shunt-compensated line is illustrated using an electromagnetic transient simulation. A temporary Phase-A-to-ground fault was simulated on an 80 percent compensated line. After the three-phase open time interval expired, the autoreclosing of each phase was attempted at different instances of the beat minimum voltage across the breaker.

Simulation results are provided in Fig. 8. The sequence of events simulated and the issues encountered are explained as follows:

- A Phase-A-to-ground fault occurs at t = 0 and is cleared by the line protection in approximately 50 milliseconds (after the line breaker opens). The fault arc extinguishes at t = 300 milliseconds (not visible in the traces).
- In Fig. 8a, the faulted phase (Phase A) voltage remains zero during and after the fault, following the line breaker opening. The unfaulted phases (Phases B and C) maintain the source voltage during the fault and start to ring down with a beat period of about 155 milliseconds after the breaker opens. The ringdown voltages decay during the three-phase open interval due to resistive losses in the open line and connected reactors.
- After a 28-cycle (almost 500-millisecond) three-phase open interval, POW-controlled closing was simulated to attempt the closing of each phase at the beat minimum. Fig. 8b shows the voltage across the breaker for each pole. Phase B closes first at t = 536 milliseconds. In Fig. 8c, there is some dc offset current in the reactor even when Phase B closes at the beat minimum due to the decaying non-60 Hz ringdown voltage. In Fig. 8d, the missing zero-crossings from this small dc component disappear shortly, approximately 32 milliseconds after Phase B closes.
- Once Phase B is energized, the beat pattern on Phase C changes due to interphase coupling. A single-phase energization of a highly shunt-compensated line creates resonant overvoltages[8] on the floating phases A and C, which are yet to be closed [11] [12]. The waveform traces show voltages reaching up to 4 pu, but in real-life scenarios, overvoltages are limited by surge arresters and magnetic saturation, which were not modeled. In a separate event reported in Section III.B, voltages of more than 1.6 pu on the two floating phases were observed under similar conditions.
- The next beat minimum occurs for Phase C at t = 995 milliseconds. As mentioned previously in Section II.C.2, the POW controller would have switched to the backup mode upon failing to detect the next beat minimum in approximately 100 milliseconds after closing the first phase to prevent an extended duration of line energization on fewer than three phases. In the simulation, the backup mode was not implemented to illustrate the behavior of the dc current when the second phase closes at the beat minimum. A large magnitude difference between the source and resonant line voltages introduces a high dc offset in the Phase C reactor current. The missing zero-crossings in the line current last a long time, about 1.37 seconds.
- At t = 1,032 milliseconds, Phase A closes at the beat minimum, introducing missing zero-crossings in the line current for approximately 130 milliseconds.

As evident from this simulation, a three-phase POW-controlled close encounters significant challenges due to the competing factors of missing current zero-crossings, resonant overvoltages, and complex beat patterns.

[5] The POW sends a close ahead of the beat minimum, compensating for the time it takes for the breaker to make its power contacts after receiving the close command.

[6] BC Hydro uses a delay of around 100 to 120 milliseconds.

[7] Overall, the three-phase open condition comprises the sum of the open time interval, the POW to detect the beat minimum, and the breaker to close its power contacts.

[8] In a high shunt-compensated line where the neutral of the shunt reactor is solidly grounded, a series LC circuit with a tuning frequency close to 60 Hz is formed when the line is energized as single phase or two phase. High voltages can be anticipated on the floating (disconnected) line conductors.

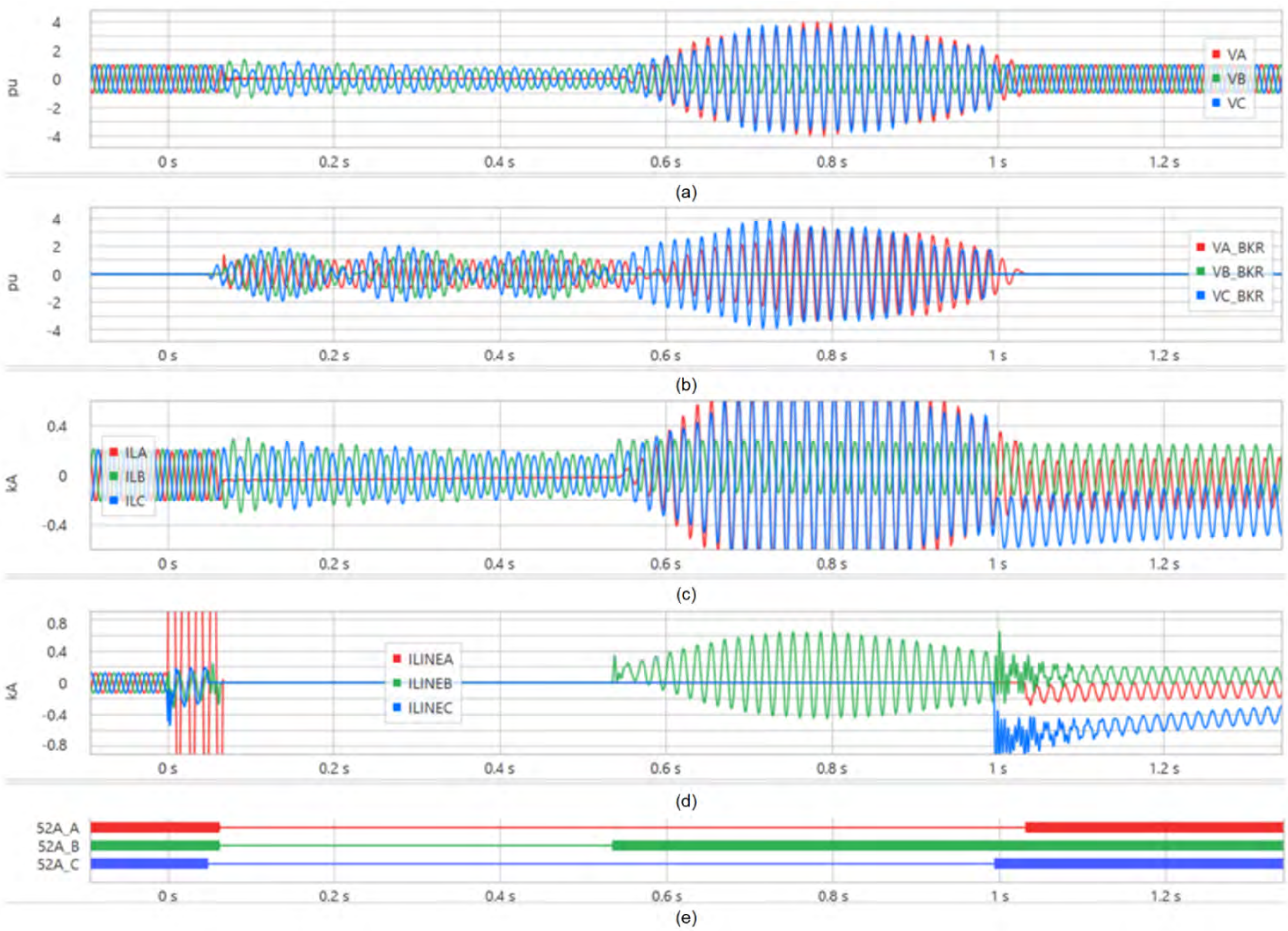

Fig. 8. Missing current zero-crossings, significant overvoltages, and complex beat patterns in a simulated 80 percent shunt-compensated EHV line. Analog traces from top to bottom: (a) line voltages, (b) voltages across the breaker, (c) inductor currents, and (d) line currents.

III. Failures and Event Analysis

BC Hydro experienced five breaker failures, all of which were associated with highly shunt-compensated lines. These failures occurred when attempting to interrupt the line current after protection operated during manual or automatic line energization. Fig. 9 illustrates a generic one-line diagram of a 500 kV line configuration with shunt compensation. Four of the failures occurred in lines that also had a midline series capacitor (for series compensation). However, the series capacitor was irrelevant to the failures because it is bypassed on all phases after the three phases of the line open.

The line is equipped with two shunt reactors, one at each terminal. These reactors are standard-sized, rated 135 MVAR at 525 kV, commonly used by BC Hydro. Together, the reactors draw an inductive current that exceeds 50 percent of the line's capacitive charging current. During heavy line loading, one reactor can be switched out to regulate the terminal voltage. Typically, both reactors are connected to the line during energization to keep the Ferranti voltage in check at the follow terminal.

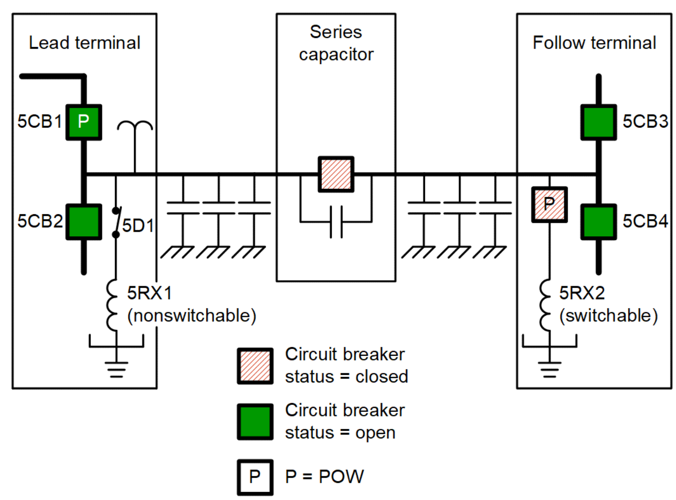

Fig. 9 Generic one-line diagram of the 500 kV lines involved in failure events. The series capacitor was bypassed and not relevant.

This section provides a brief description of the sequence of events leading to the breaker failures and utilizes recorded waveforms to demonstrate how the failures resulted from the lack of zero-crossings in the line currents during energization. Instead of redrawing a one-line diagram for each failure event, the paper references back to Fig. 9, which includes pseudodesignations of line terminals, breakers, and reactors. The focus is to present the sequence of events leading to the absence of zero-crossings in the line current, which is the root cause of the failures.

A. Event A: Failure After Reactor Protection Tripped

The failure occurred on May 14, 2021, on a 500 kV line, which spans 277 km and is 72 percent shunt-compensated by two reactors. Table I lists the shunt-compensation parameters. The breaker failure occurred shortly after manual energization of the line from the lead terminal using POW-controlled closing of 5CB1, as shown in Fig. 9. The controlled closing of 5CB1 for line energization was optimized to minimize switching voltage transients and set to close at the source voltage zero-crossing for the manual line energization assuming the line had no trapped charge. This energization marked the first operation of the line after the installation of a new reactor and associated protection systems, which replaced the old ones at the end of their service life. During the line energization, one of the reactor protections operated incorrectly.

TABLE I
LINE SHUNT-COMPENSATION PARAMETERS

Positive-Sequence Line Shunt Parameters	
Shunt Admittance (Y1)	1,387 µ℧
Capacitive Reactive Power	374 MVAR at 525 kV
Capacitive Current	411 A
Lead and Follow Terminal Shunt Reactor Parameters	
Reactor Size	135 MVAR at 525 kV
Inductive Current	148.5 A
Positive-Sequence Compensation Parameters	
Percentage Compensation	72%
Compensated Line Charging Current at Lead Terminal	114 A

Fig. 10 details the sequence of events. One cycle after the line energization from 5CB1, the high-impedance differential protection (87R) of 5RX1 operated. The 5CB1 power contacts physically opened on all three phases after receiving the protection trip, but only Phase B interrupted the current. Because there was no fault, the shunt-compensated line charging current was below 300 A, which is the relay's minimum breaker failure protection pickup setting. Hence, 5CB1 breaker failure protection was not activated. The Phase C current was eventually interrupted more than 21 cycles after trip initiation. However, the current in Phase A continued to flow. Approximately 10 seconds after the trip initiation, 5RX1 differential protection sent an open command to the disconnect (5D1) to isolate the reactor. Since the uninterrupted Phase A current was still flowing in 5RX1 when the disconnect was opening, a large arc formed and flashed to the steel structure, causing a low-resistance line-to-ground fault. This fault allowed the line protection to trip, resulting in the de-energization of the line and the associated reactor due to the activation of the breaker failure protection because the resulting fault current was above the breaker failure pickup setting.

Fig. 11 displays waveforms of the three-phase line currents and source voltages at the lead terminal. Phase B closed first, approximately 1.1 milliseconds after a bus voltage zero-crossing. Phase A closed about 0.5 milliseconds after a bus voltage zero-crossing, and finally, Phase C closed approximately 0.5 milliseconds after a bus voltage zero-crossing. It should be noted that, compared to the programmed settings, the closing performance on Phase B was the worst, while the closing of Phases A and C occurred close to their target points. These discrepancies were likely due to mechanical dispersion in the operation times of the circuit breakers. For breakers with POW-controlled switching schemes, a closing time accuracy of ±1 millisecond (corresponding to three standard deviations) is generally considered acceptable [2] [9]. Overall, the near zero-degree closures on Phases A and C resulted in the observed high dc offset current.

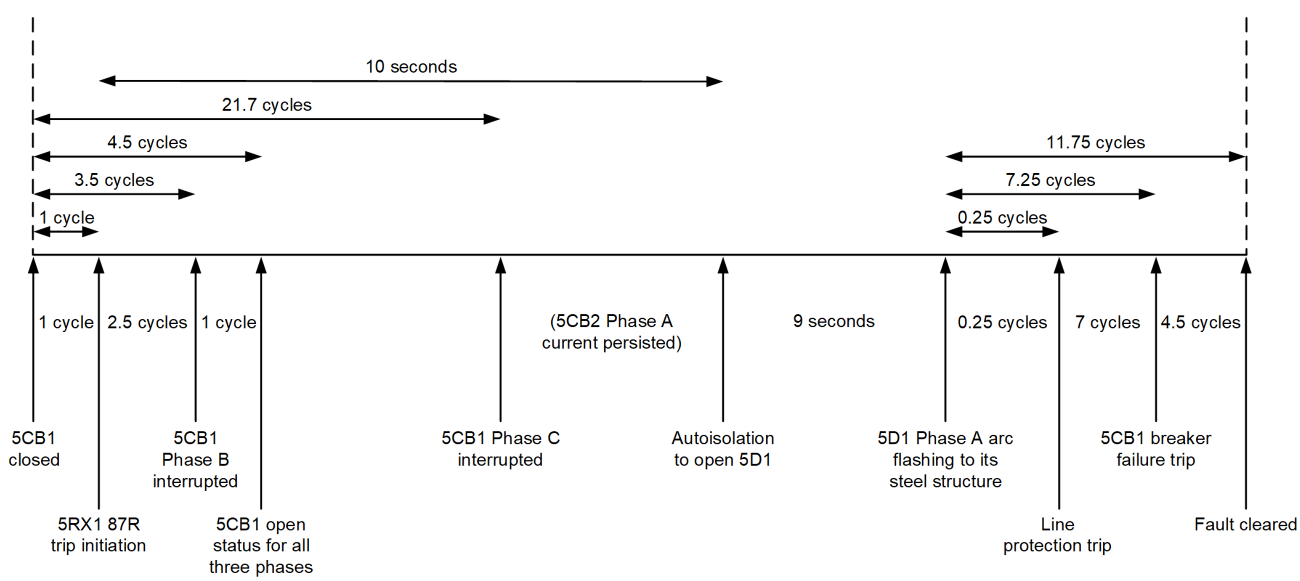

Fig. 10. Detailed sequence of events during the failure of the 5CB1 breaker at the lead terminal on May 14, 2021.

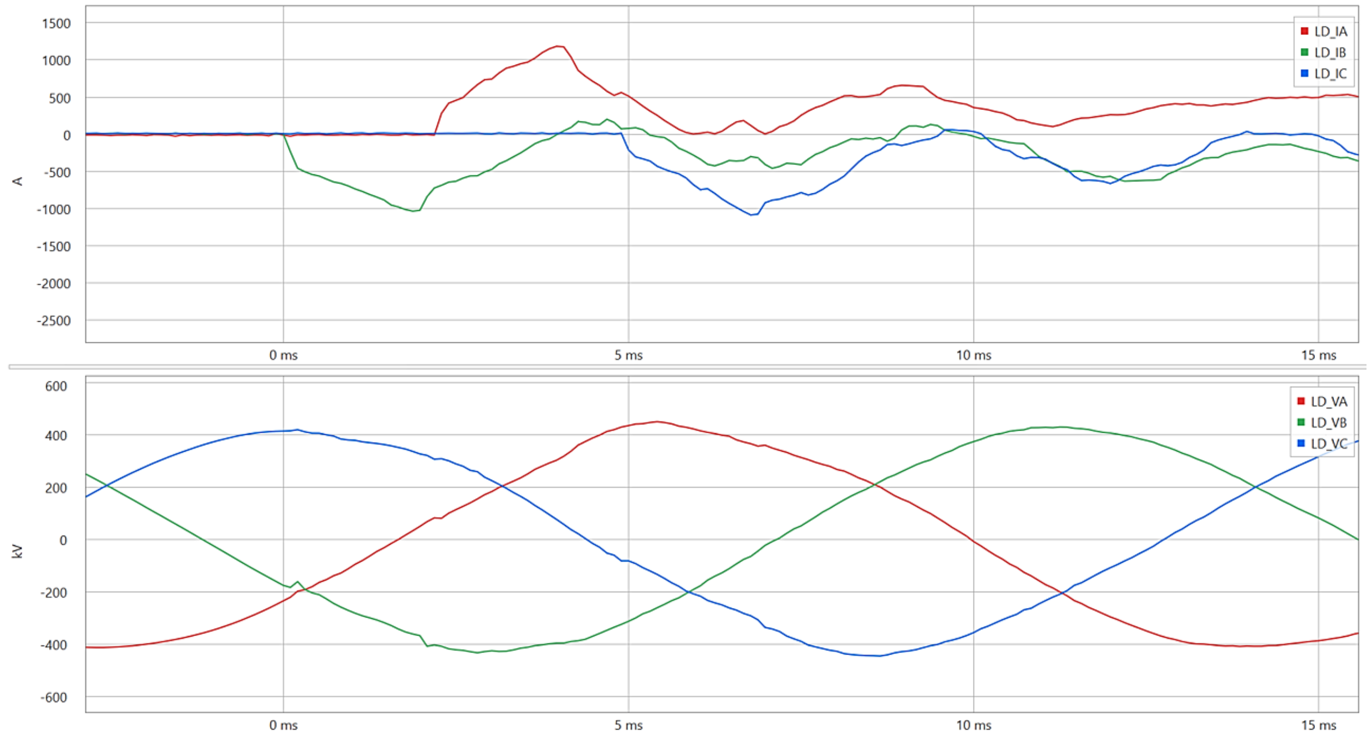

Fig. 11. Three-phase line currents and voltages at the lead terminal during manual energization via POW on May 14, 2021.

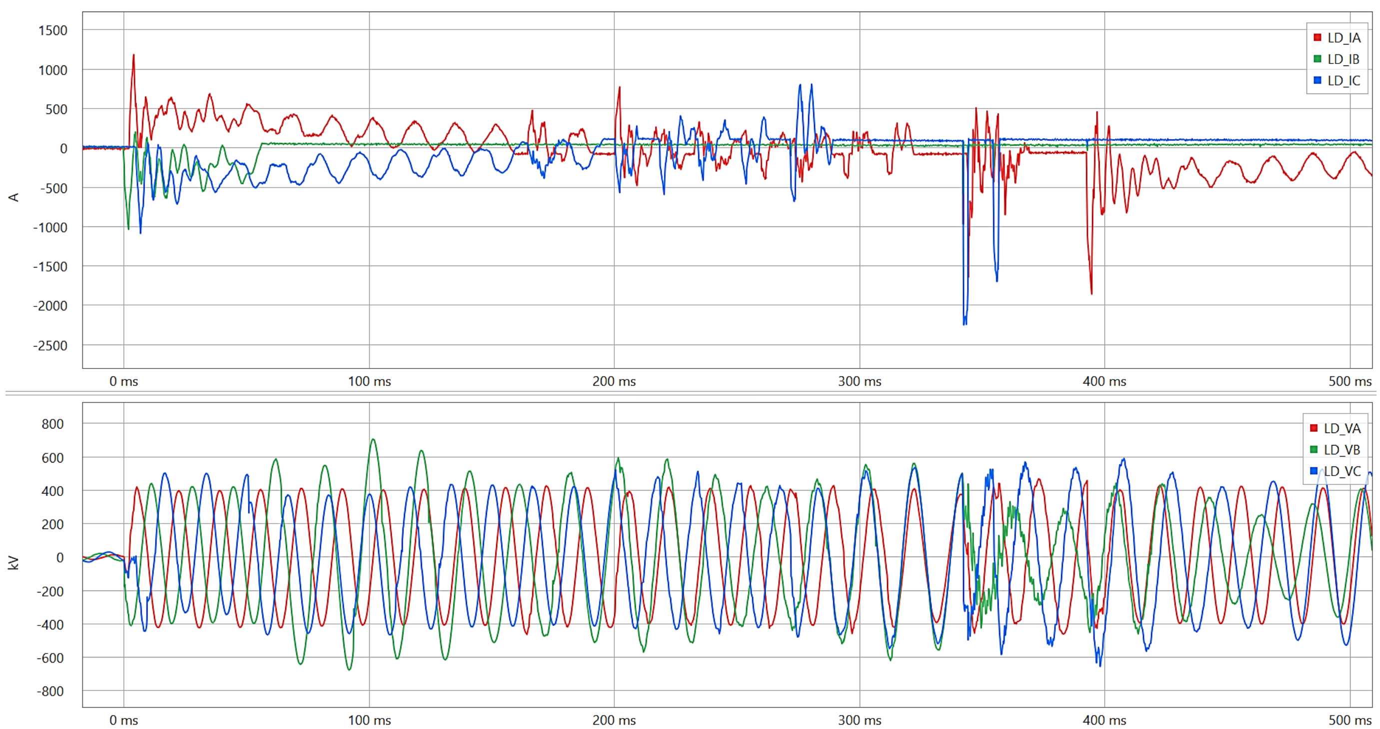

Fig. 12. The first 30 cycles of 5CB1 currents and terminal voltages after breaker closing on May 14, 2021.

As shown in Fig. 12, all three phases of 5CB1 currents exhibited high dc offsets. There were no zero-crossings on Phases A and C for approximately 9 cycles after the closing of 5CB1. Two zero-crossings were observed on Phase B, and the current was successfully interrupted within 3 cycles. Phase C current was finally interrupted after approximately 21 cycles from the trip, after multiple contact restrikes. However, Phase A failed to interrupt the current, and the current in Phase A persisted. The nearly perfect performance achieved by the POW control, designed to minimize voltage transients, caused the missing current zero-crossings, which persisted even after 30 cycles from the line energization. These missing zero-crossings were the root cause of the breaker failure when the protection incorrectly tripped during line energization.

B. *Event B: Breaker Failure After Line Protection Trip From Wide Pole Scatter*

The failure was on a parallel line to the one discussed in Section III.A with the same parameters as in Table I. It happened after an incident on April 16, 2012. Table II provides a detailed sequence of events set in motion by an improper protection isolation and shorting procedure during line CT replacement. The lead and follow terminal voltage and current waveforms and digitals are shown in Fig. 13. The entire sequence, from an inadvertent trip to complete line isolation, lasted approximately 6.8 seconds. By the end of this sequence, one breaker and two surge arresters had failed.

The incorrect isolation and shorting of the CT under the load caused the primary protection of the line to operate, tripping the lead terminal and sending a DTT to the follow terminal. After the line trip from both terminals and the expiration of the three-phase open time interval, the high-speed autoreclose was initiated. At the lead terminal, the POW controller reclosed Phases B and C, but the closing of Phase A was delayed due to the POW algorithm facing challenges in predicting the beat minimum and its switch to backup mode. Phase A reclosed suboptimally, not at the beat minimum, by about 90 milliseconds. Immediately after Phase A closing, the high-speed distance (Zone 1 phase mho) element within the line standby protection transiently picked up and initiated the line trip. Another DTT was sent to the follow terminal.

TABLE II
SEQUENCE OF EVENTS TRIGGERED BY PERSONNEL INCIDENT

Order	Timestamps (Milliseconds)	Event
1	0	Unintentional trip of the line primary protection at the lead terminal
2	700	Autoreclose of Phases B and C at the lead terminal
3	790	Reclose of Phase A at the lead terminal
4	800	Line standby protection undesired operation at the lead terminal; trip initiation during autoreclose and transmission of direct transfer trip (DTT) to the follow terminal
5	810	Reclose and trip (trip-free) operation of 5CB3 at the follow terminal
6		At the follow terminal, 5CB3 Pole A failure to interrupt the line current on trip
7		Follow terminal Phase B surge arrester failure from resonant overvoltage
8	5,780	Lead terminal Phase A surge arrester failure, causing the ground fault
9	6,620	Trip initiation at the follow terminal by timed ground fault protection
10	6,730	5CB3 breaker failure trip
11	6,790	Line isolation at the lead terminal by the trip of the adjacent breaker

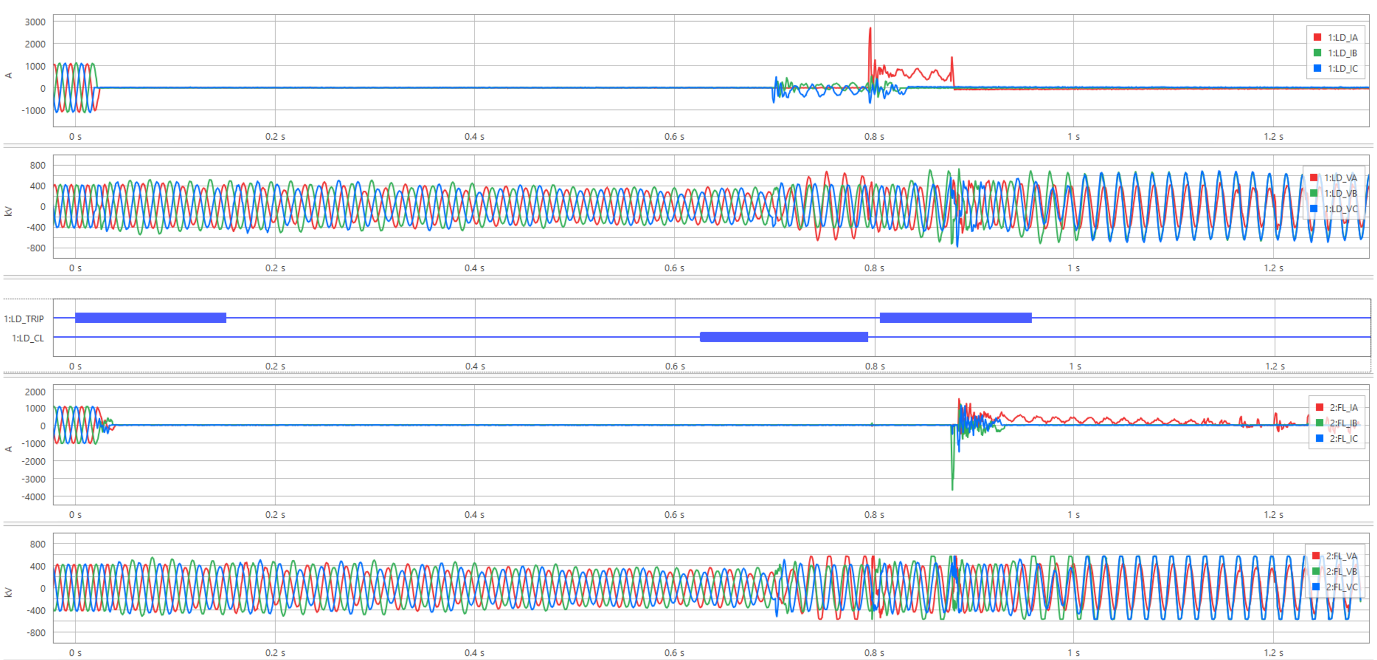

Fig. 13. Protective relay records showing the Event B sequence in the lead and follow terminals. (Note: the follow terminal digitals are not available.)

During the short period where all three phases were closed at the lead terminal, the line developed sufficient positive-sequence voltages[9] to initiate the autoreclose at the follow terminal before the arrival of the DTT. Consequently, 5CB3, the first breaker to close at the follow terminal, experienced trip-free operation, meaning it closed and tripped since it received the DTT from the lead terminal. In Fig. 13, the waveforms and digitals illustrated were recorded by the standby protective relay, which tripped during wide pole scatter created by POW-controlled closing at the lead terminal during the autoreclose. Wide pole scatter refers to the long delay (about 100 to 120 milliseconds) from the first to the last phase closing from POW-controlled close.

During the trip immediately upon autoreclose at the follow terminal, Phase A of circuit breaker 5CB3 failed to interrupt the current even though the breaker contacts had physically opened. The uninterrupted phase continued to conduct, keeping one phase of the line energized. This single-phase energized, highly shunt-compensated line created a resonant condition [13] [14], resulting in excessive voltage buildup on the floating phases and causing the Phase B surge arrester to fail from extended exposure to overvoltage. Approximately 6 seconds after the initial trip, the Phase A surge arrester protecting the shunt reactor at the lead terminal failed due to sustained multiple restrikes across the physically open circuit breaker, with an uninterrupted current from missing zero-crossings. The surge arrester failed, leading to a short circuit condition that caused a permanent line-to-ground fault and triggered the breaker failure protection to operate, clearing the fault and isolating the line. Fig. 14 shows the damage. The top picture shows the failed surge arrester, while the bottom photos show the damage to the interrupter mechanism inside the breaker due to the prolonged arc.

Fig. 14. The catastrophic failure of April 16, 2012.

C. *Event C: Failure After Temporary Lightning Fault*

The failure occurred on a 330 km, 500 kV line with shunt compensation provided by two shunt reactors at the line terminals, as depicted in Fig. 9. On July 12, 2016, the line experienced a temporary Phase-B-to-ground fault induced by a lightning strike. The line protection system correctly tripped all three phases, de-energizing the line. During the three-phase open time interval, the fault arc was extinguished. After the open-pole interval time, the lead terminal breaker (5CB1) was closed using POW control. However, after 1.5 cycles, the Zone 1 phase mho relay unexpectedly asserted for under 2 cycles, tripping the lead terminal and issuing a DTT signal to the follow terminal. Fig. 15 presents records captured by the relay at the lead and follow terminals. It demonstrates the line voltage ringing down before autoreclose, the activation of phase distance protection elements, and the significant dc offsets in the unfaulted phase currents after the line was re-energized on autoreclose.

At the follow terminal, the DTT signal was received after its autoreclose had already been asserted. The close command to 5CB3 was sent 11 milliseconds before the DTT was received. By the time 5CB3 closed at the follow terminal, 5CB1 at the lead terminal had already tripped[10] and successfully interrupted the line currents because the POW had closed all three at around the beat minimum. However, 5CB3 does not utilize a POW or pre-insertion resistors. This resulted in an uncontrolled close onto the line ringdown voltage, and the three poles of the breaker closed at different points on the voltage waveform, inducing different levels of dc offset current in each phase. Notably, the Phase C current had the highest dc offset.

Once the follow terminal closed, it immediately tripped free due to the transfer trip. The circuit breaker contacts physically opened, but the current could not be interrupted until the next zero-crossing. The Phase A current was distorted with no dc offset, resulting in the breaker interrupting 3 cycles after closing. The Phase B current had a higher dc offset but achieved a zero-crossing and interrupted 6 cycles after closing. However, Phase C, with the highest dc offset current, did not experience a zero-crossing until 28 cycles later. By this point, the circuit breaker no longer had the capacity to interrupt the arc and restrikes continued to occur. The arcing and restriking lasted approximately 18 seconds and only ceased when the circuit head failed catastrophically. The pressure relief vents in the breaker did not operate but continued arcing inside the interrupting chamber, heating the porcelain to the point at which it shattered. Fig. 16 shows the damage.

[9] In the autoreclose cycle after the expiration of the open-phase interval, the logic requires positive-sequence voltage to be more than 90 percent of the nominal voltage, before committing to the autoreclose of the follow terminal.

[10] There was a race between the opening of 5CB1 at the lead terminal and the closing of 5CB2 at the follow terminal. Since the breaker closing times are much longer than opening times, the opening of 5CB1 occurred before the closing of 5CB2.

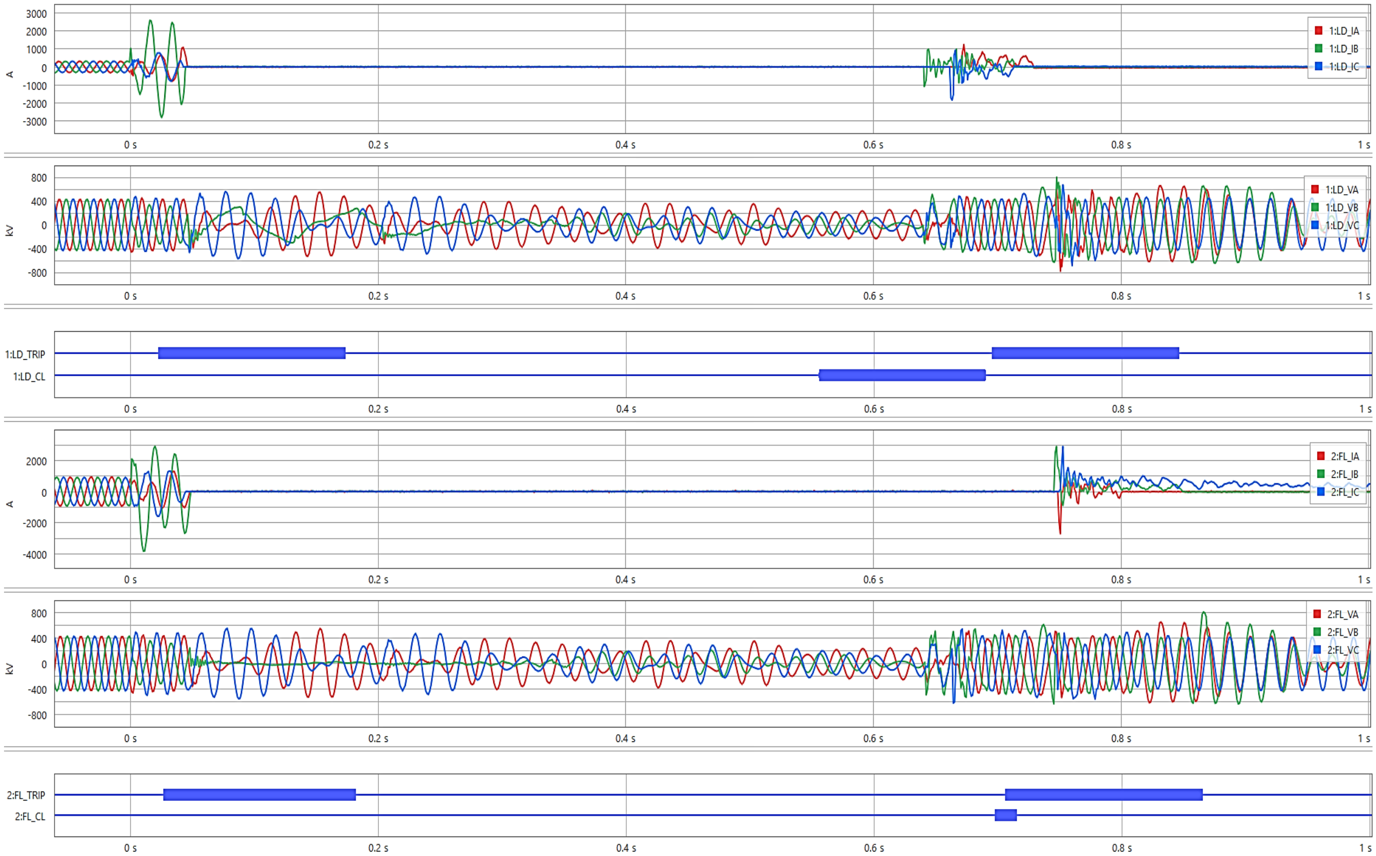

Fig. 15. Protective relay records showing the Event C sequence in the lead and follow terminals.

Fig. 16. The catastrophic failure of July 12, 2016.

In the figure, the top left picture shows the grading capacitor, which used to be in parallel with the failed interrupter. The bottom left picture shows the moving contact from the failed interrupter. The figure on the right shows the fixed contact from the failed interrupter hanging in the center of the picture.

Despite the failure to interrupt the current, the breaker failure protection did not activate for two reasons. First, the ac component of the breaker current was approximately 180 A, which was below the breaker failure relay pickup setting of 300 A. Second, the breaker failure initiation signal from the line protection dropped out 9 cycles after the transient keying of the Zone 1 phase mho element at the lead terminal.

D. Event D: Failure During POW Field Testing

On May 13, 2022, a breaker failure occurred during the POW field testing, which involved the energization of a 329 km, 500 kV line. Two shunt reactors, located at each end of the line, provided 59.8 percent shunt compensation. The testing was conducted for the POW controller, which was specifically associated with 5CB1, as shown in Fig. 9. Online POW controller testing is a standardized procedure required to calibrate the POW to detect beat minimums for in-service conditions and is used for commissioning purposes at BC Hydro.

Before the testing commenced, the line was connected to the system with its breakers closed and the series capacitor was bypassed. As per the standard test procedure, the primary line protection settings at the lead terminal were modified to force a three-phase trip on the healthy line and initiate autoreclose. This modification allowed for the calibration of the POW settings for the line autoreclosing. As planned, the primary protection tripped, opened all line breakers, and initiated autoreclose when the testing began.

After the three-pole open interval, which lasted slightly less than 0.5 seconds (28 cycles), the autoreclose was asserted at the lead terminal by issuing the close command to 5CB1 through the POW controller. Upon receiving the close commands, Phase A of circuit breaker 5CB1 took 107 milliseconds (about 6.4 cycles) to close. Phase B required an additional 44 milliseconds, and after another 14 milliseconds, Phase C closed. In total, it took approximately 165 milliseconds (around

10 cycles) to close all three phases of 5CB1. These time durations include both the POW logic time and the breaker's closing time. The long dispersion in closing times between phases (or wide pole scatter) was introduced by the POW controller's attempt to locate beat minimums to minimize voltage transients during each phase's closing. However, during the closing of 5CB1 by POW control, there was an undesired operation of the line protection at the lead terminal. The Zone 1 phase mho protection momentarily picked up for 2 milliseconds and retripped the line, causing 5CB1 to open. After 67 milliseconds, the line protection initiated a DTT signal to the follow terminal. The open terminal logic triggered this signal.

In Fig. 17, three-phase voltages and currents recorded by the line protection relays at the lead and follow terminals are displayed. While the closing operation was still in progress at the lead terminal due to the POW controller, a healthy positive-sequence voltage had developed on the line. This allowed the autoreclosing at the follow terminal to proceed with the close command to 5CB3 before the arrival of the DTT signal. Breaker 5CB1, tripped by the Zone 1 phase mho element, opened before 5CB3 could close. Fortunately, there was no dc offset or loss of zero-crossings in the line currents when 5CB1 closed because of POW-controlled closing at the beat minimums.

The breaker 5CB3 at the follow terminal closed 19 milliseconds after 5CB1 at the lead terminal opened. Because there is no POW control at the follow terminal, the close command to 5CB3 resulted in the simultaneous closing of all three phases, leading to an uncontrolled re-energization of the line from the follow terminal. Consequently, a significant dc offset was present in the line current once 5CB3 closed on all three phases simultaneously, causing missing current zero-crossings on all three phases for a duration of 170 milliseconds. During this time, the follow terminal received the DTT signal sent by the open terminal logic at the lead terminal. Due to the missing zero-crossings, 5CB3 failed to interrupt the current, resulting in catastrophic breaker failure. As explained previously, the breaker failure protection did not operate because the compensated line charging current was too low to be detected. This condition persisted for 12 seconds before a Phase-B-to-ground fault occurred, which activated the breaker failure protection and tripped the adjacent bus zone. Fig. 18 shows the damage.

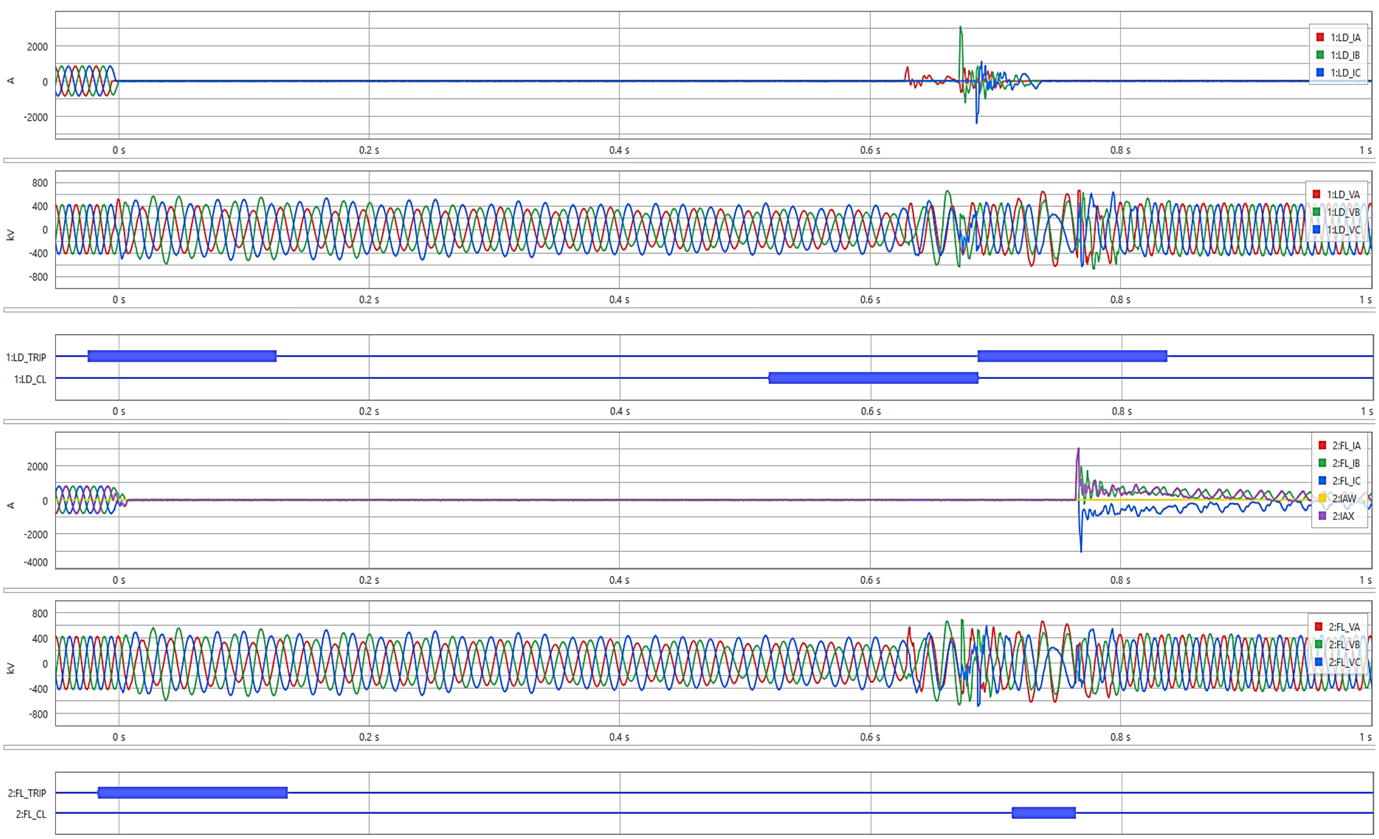

Fig. 17. Protective relay records showing the Event D sequence in the lead and follow terminals.

Fig. 18. The catastrophic failure of May 13, 2022.

E. Event E: Failure During Permanent High-Impedance Fault

This breaker failure occurred on a 500 kV transmission line that is 197 km long. As shown in Fig. 9, this line has two shunt reactors that overcompensate the line's capacitive charging current to 103.6 percent because the line is relatively short. Hence, the switchable reactor is automatically disconnected at the beginning of the three-phase open interval after every line trip. The disconnection of one shunt reactor brings down the compensation to half level (51.8 percent) prior to line re-energization. In this particular line, 5CB1 is not equipped with a POW. It is one of the few remaining breakers at BC Hydro that still have pre-insertion resistors (300 Ω). These resistors are engaged for 8 to 11 milliseconds to switch surge control.

On January 22, 2023, the line had a high-impedance Phase-B-to-ground fault. The line protection system, which employs a permissive overreaching transfer trip scheme with a sensitive ground directional element, correctly tripped, opening all four breakers, bypassing all three phases of the series capacitor, and initiating the autoreclose sequence. Additionally, as intended, the line protection system opened one of the two shunt reactors (5RX2).

Following a three-pole open interval of 28 cycles, the lead terminal issued a close command to 5CB1. Since it was a permanent fault, the lead terminal was retripped by switch-onto-fault (SOTF) logic after 5CB1 autoreclosed. Fig. 19 shows synchronized recordings of the line protection relays at the lead and follow terminals during the autoreclose event. Due to the high-impedance nature of the fault, the line exhibited a healthy positive-sequence voltage (above 90 percent of the nominal voltage) at the follow terminal for the duration after 5CB1 reclosed and before it retripped by SOTF logic. This allowed autoreclosing to proceed at the follow terminal by sending a close command to 5CB3. However, the actual closing of 5CB3 at the follow terminal occurred only after 5CB1 had opened at the lead terminal,[11] resulting in the uncontrolled closing of all three phases simultaneously. Shortly thereafter, the follow terminal received the DTT signal from the lead terminal, initiated by open terminal logic. The uncontrolled closing of 5CB3 at the follow terminal introduced a high dc offset with missing zero-crossings in the unfaulted phases, and the breaker did not have a chance to interrupt the current in those two unfaulted phases. The breaker failure protection did not operate because the unfaulted phases were carrying only compensated line charging current, which was too low to be detected by the breaker failure protection. Once the dc current component dissipated, the breaker was no longer able to operate. This condition persisted for a period of 18 seconds before a Phase-A-to-ground fault occurred, triggering the operation of the breaker failure protection and tripping the adjacent bus zone. Fig. 20 shows the damage.

[11] 5CB1 uses pre-insertion resistors for closing and opening, which reduces dc offset in line energization currents and helps to achieve successful interruption on line de-energization.

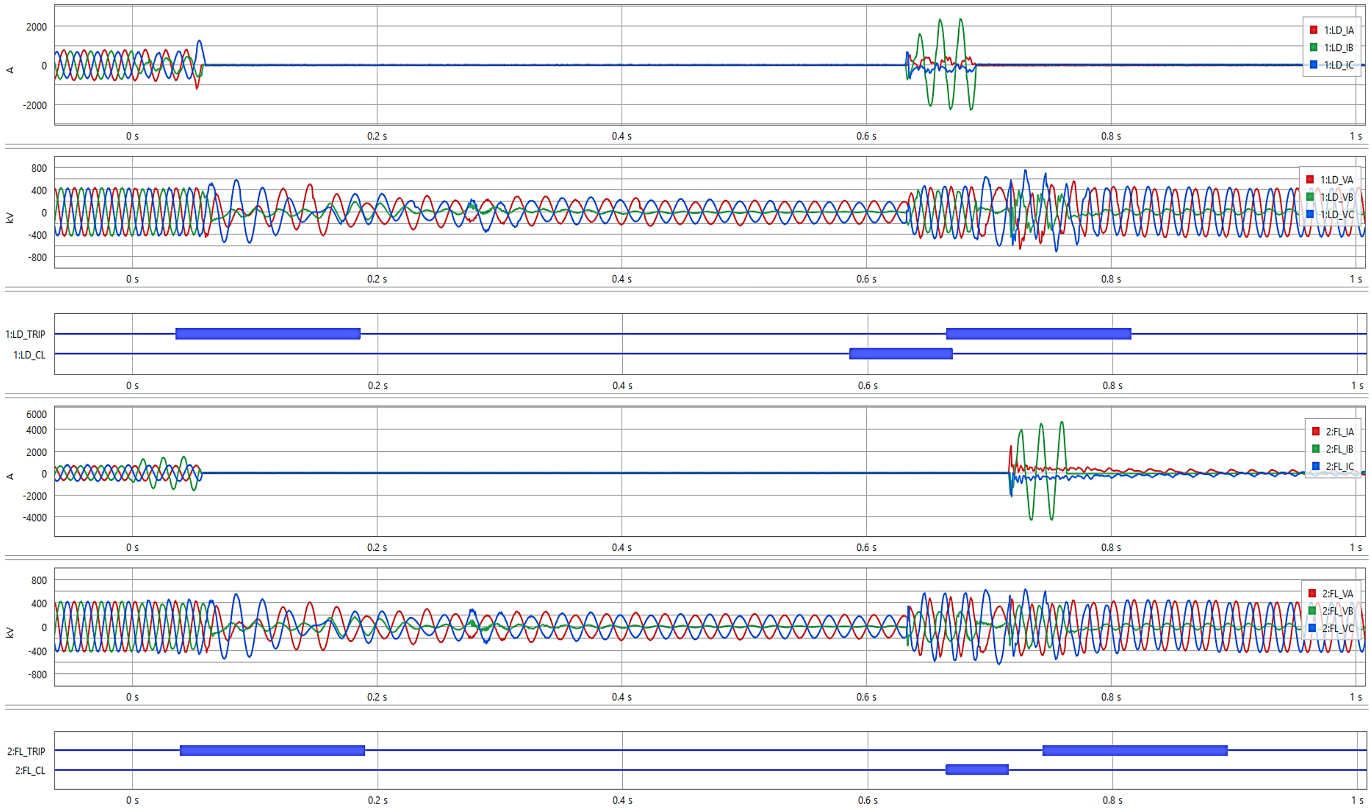

Fig. 19. Protective relay records showing the Event E sequence in the lead and follow terminals.

Fig. 20. The catastrophic failure of January 22, 2023.

IV. Lessons Learned

Table III provides a comprehensive summary of the contributing factors to the failures, offering a bird's-eye view that can help identify common factors. This section aims to discuss the lessons learned from reviewing some of these common factors.

All five failures occurred on highly shunt-compensated lines, with the root cause being the absence of zero-crossings in the line current upon line energization. The failures happened after protection tripped either correctly or incorrectly upon line energization.

In Event A, one of the failed breakers was at a lead terminal during manual line energization. In this instance, the POW control worked correctly as intended but resulted in missing zero-crossings because it was optimized solely for controlling voltage transients. The failure was caused by a misapplication of protection settings, leading to an undesired operation and eventual failure.

TABLE III
SUMMARY OF CONTRIBUTING FACTORS FOR THE FIVE FAILURES

		Events				
		A	B	C	D	E
Highly Shunt-Compensated Lines		X	X	X	X	X
Missing Current Zero-Crossings		X	X	X	X	X
Line Energization	**Manual**	X				
	Automatic		X	X	X	X
POW	**Optimal**	X		X	TBD	NA
	Wide Pole Scatter		X	X	X	
Autoreclose Supervision Logic			X	X	X	X
Protection (Undesired Operation)	**Polarized Zone 1**		X	X	X	
	Settings Error	X				
Correct Protection Operation						X

The other four failures occurred at the follow terminals during autoreclose. The missing zero-crossings were introduced due to either the POW being unable to detect the beat minimum before closing at the lead terminal or uncontrolled closing at the follow terminal. Among these four failures, one happened after a correct protection operation, but the remaining three occurred after protection undesired operations. Details about the contributing factors, along with the corrective measures, are discussed in the next section.

The autoreclose supervision at the follow terminal relies on a 90 percent positive-sequence line voltage restoration as an indication of the successful autoreclose at the lead terminal. BC Hydro employed this logic on all 500 kV lines from the beginning, but it did not function as intended. In Events B, C, and D, it allowed the follow terminal to close even though the lead terminal had tripped and opened just before the closing of the follow terminal. Similarly, in Event E, it permitted closing during a permanent high-impedance fault. A detailed discussion of the logic failure and the improvements are in the next section.

V. ROADMAP OF CORRECTIVE ACTIONS

The ongoing catastrophic failures are unacceptable and pose a safety risk to the station personnel working around highly shunt-compensated line terminals. It is crucial to implement a mitigation strategy to prevent these failures. Depending on time and capital investment to deploy, a three-stage (short-term, midterm, and long-term) roadmap of corrective actions is discussed.

A. Short-Term

The short-term corrective action was making protection settings changes, which were identified and applied after each failure event. These changes were intended to improve protection security during line energizations.

1) High-Impedance Differential Protection

In Event A, the high-impedance differential protection operated incorrectly upon manual line energization. It was thoroughly investigated with the support of the relay manufacturer, revealing that the protection was set too sensitively to account for the mismatch between the excitation characteristics of the two sets of differentially connected CTs. The differential relay pickup was increased to secure protection from mismatched CTs and high dc offset in the reactor current during energization.

Reactor differential protection can detect internal phase-to-ground and phase-to-phase faults. These faults typically result in significant differential currents [15]. Therefore, the revised reactor protection setting was set with a security bias but still provided adequate dependability for internal faults. With revised protection settings, the protection remained secure every time the line was operationally de-energized and energized, which has occurred many times since the failure event in May 2021.

2) Zone 1 Phase Mho Transient Pickup

In Events B and D, the Zone 1 mho relay transiently picked up due to wide pole scatter during autoreclose at the lead terminal. The relay utilizes positive-sequence memory voltage for the polarization quantity. In discussions with the relay manufacturer, it was found that these undesired operations were attributed to the polarizing voltage phase angles becoming transiently unstable during POW-controlled closing. This instability arises because all three phases close at different instants with durations of 100 milliseconds or greater to complete the closing. A digital filter, estimating the 60 Hz positive-sequence phasor, began calculations at the onset of the first phase closing using single-phase voltage. As the other two voltages became available, it started to incorporate them in the phasor estimate and experienced a transient response after each phase closing, resulting in Zone 1 momentarily picking up.

To address the issue following Event B, a quarter-cycle delay was added to the Zone 1 phase mho element of the line protection. However, after encountering another transient pickup in Event D, this delay has now been extended to all highly shunt-compensated lines as a security measure against transient pickup. Despite this additional delay, BC Hydro's transmission system performance target of clearing multiphase faults within 4 cycles for the overall clearing time is still maintained.

3) Zone 1 Polarizing-Memory Voltage Corruption

In Event C, the Zone 1 phase mho relay unexpectedly operated upon autoreclose where a temporary fault arc had extinguished during the three-phase open time interval. The element remained asserted for about 2 cycles at the lead terminal. The undesired operation was traced back to the

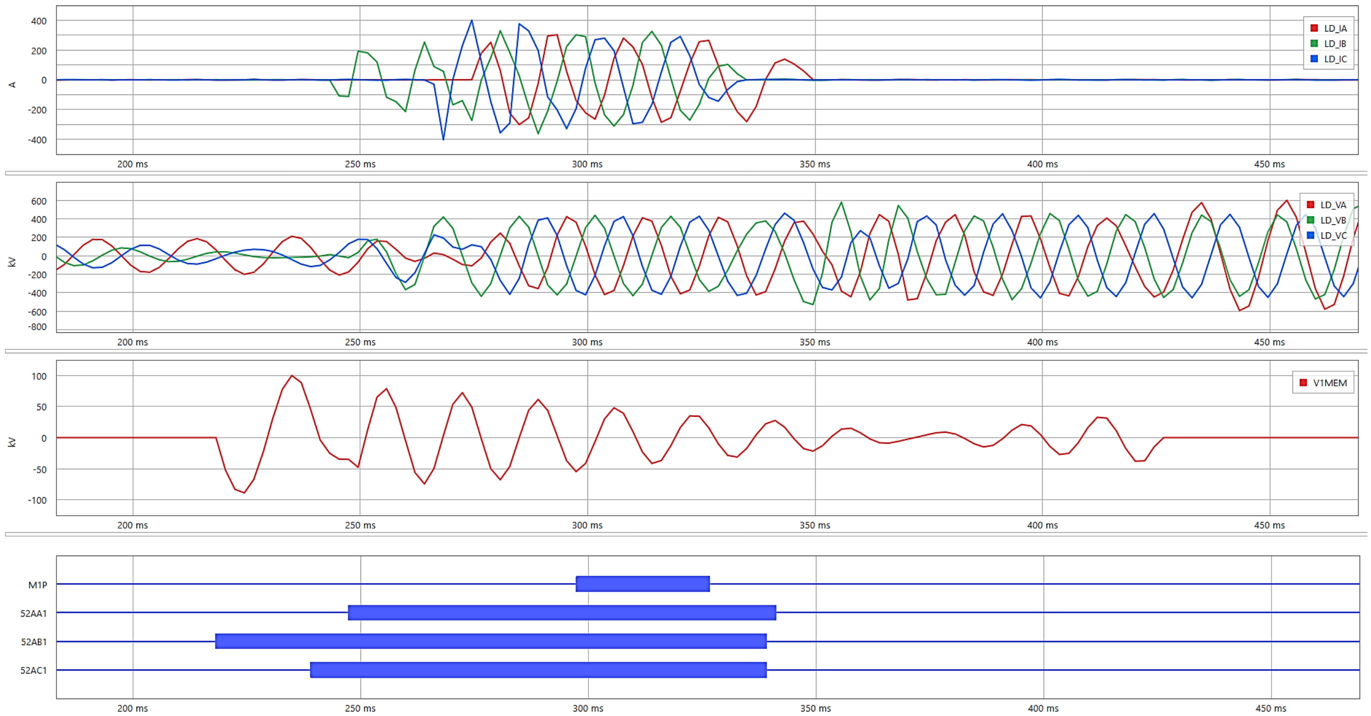

Fig. 21. The relay event record at the lead terminal showing memory charging upon closing of the auxiliary contact but before closing of the main power contacts on July 12, 2016.

opening of the breaker auxiliary contact, 52b,[12] approximately 2 cycles before the corresponding power contact closure (see Fig. 15). This led to an incorrect phase angle of the positive-sequence memory voltage relative to the source voltage when the line was autoreclosed.

Fig. 21 demonstrates how the relay memory began to charge with unreliable positive-sequence voltage approximately 2 cycles before the breaker power contacts closed. The protection relays used on this line have a feature in which polarizing voltage is rapidly memorized (with a short time constant) after line closure, after which the relay switches to a longer time constant. Since the 52b (auxiliary contact) closed before the power contacts, the relay's polarization voltage was, in fact, the memorized line ringdown voltage and was approximately 135 degrees out of phase with the actual system positive-sequence source voltage. As the power contacts closed and the polarization voltage swung around to the correct value, the expanded relay characteristic swung around as well and eventually encompassed the operating point.

BC Hydro's standard protection system design at 500 kV utilizes 52b contacts to monitor the circuit breaker power contact status. During a breaker close sequence, the 52a contacts close after the power contacts while the 52b contacts open before the power contacts close. The reverse occurs during a trip operation, with the 52a contact changing state early and the 52b contacts changing state after the power contacts. A potential solution would involve modifying the relay's power contact status indicator logic to consider both auxiliary contacts: 52a and 52b.

[12] 52b is an auxiliary contact that provides the inverse status of the power contact. When the power contact is closed, 52b is open, and vice versa, but 52b opens slightly before the power contact closes.

Fig. 22 demonstrates AND logic for driving the main power contact status within the relay utilizing 52a and 52b. Fig. 22a and Fig. 22b provide the close and open statuses of the power contacts, respectively. By using the power contact status from Fig. 22a, the relay's memory would start charging correctly from the polarizing voltage after the line is connected to the source voltage, rather than incorrectly from the ringdown voltage before closing the power contacts when relying solely on 52b statuses. However, implementing this solution in the BC Hydro application was not feasible due to the presence of two 500 kV breakers at each line terminal, with each breaker consisting of three single-phase breakers. Wiring six additional inputs for 52a statuses would be required, which was impractical given the lack of available spare digital inputs on these relays. As an alternative, a 3-cycle delay was applied to the 52b contacts using the built-in debounce timers in the relay.

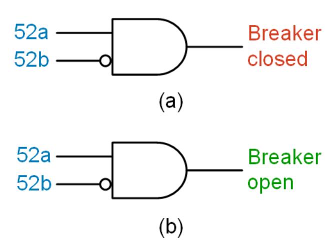

Fig. 22. Use of both breaker 52a and 52b contact inputs for the secure indication of a) the breaker opening and b) the breaker closing.

B. Midterm

The corrective actions being considered for the midterm plan do not require significant capital investment but are being evaluated for implementation on all highly compensated lines. These corrective actions include potential options to reduce the dc offset current, such as temporarily reducing shunt compensation before line energization or making modifications to the POW targets. Additionally, a new logic for follow terminal autoreclose supervision has been developed to enhance the voltage supervision and prevent the reclosing of the follow terminal when the lead terminal retrips during autoreclose. Furthermore, a logic improvement to enhance the security of Zone 1 phase mho protection has been proposed. Both the reclose supervision and Zone 1 security logic were developed in collaboration with the relay manufacturer during the preparation of the paper. The proposed logic will undergo type testing and will be implemented after successful testing.

1) Reducing Compensation During Line Energization

The root cause of the failures was the occurrence of missing zero-crossings. These missing zero-crossings are introduced when the line is highly shunt-compensated, with compensations exceeding 50 percent, and during line energization. To address this issue, the possibility of disconnecting one of the switchable line reactors was explored for both manual and automanual reclose operations.

By disconnecting one reactor, the shunt compensation drops below 50 percent for all cases except the line involved in Event E. This corrective action is highly desirable as it eliminates the risk by altogether eliminating the occurrence of missing zero-crossings. BC Hydro's operating order now incorporates disconnecting the switchable reactor during manual energization. However, implementing this action requires careful preparation by the operator to ensure that the open terminal voltage rise from the Ferranti effect remains below 550 kV, the maximum operational limit, and does not trigger the overvoltage protection to operate. At BC Hydro, the first stage overvoltage protection begins at 570 kV with a time delay.

The possibility of opening the shunt reactor during autoreclose was considered but deemed unviable. This is because autoreclose is applied after line faults, which introduce missing zero-crossings in the currents of the reactor breaker throughout the three-phase open time interval [16]. Fig. 23 displays waveforms obtained from a simulation conducted using an electromagnetic transient program. In this simulation, a Phase-A-to-ground fault was applied on a highly shunt-compensated line near one of the line terminals, resulting in a significant voltage depression. The fault was applied when the Phase A voltage was at a 60 degree phase angle after the positive zero-crossing.

The reactor in the faulted phase exhibited a high offset current with a very long decay time constant, leading to the persistence of missing zero-crossings. Switching out the reactor during the three-phase open interval following a line fault would be counterproductive and would increase the risk of a reactor breaker failure.

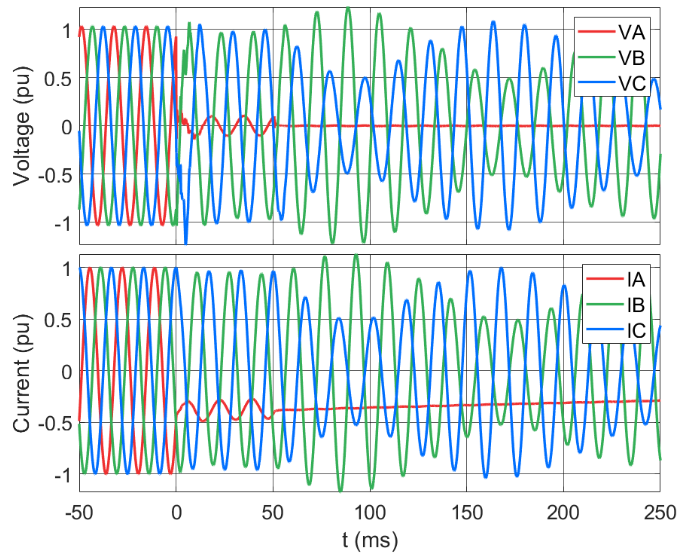

Fig. 23. Missing zero-crossings in the reactor current after a line Phase A-to-ground fault.

2) Modifying POW Targets for Manual Line Energization

To manually energize the line with one shunt reactor disconnected, additional countermeasures are required to limit the open terminal voltage rise below 10 percent nominal voltage, i.e., 550 kV. However, during lightly loaded or weak source system conditions, it is impractical to have open terminal voltage (within limits) with only one line reactor connected. As an alternative strategy, the possibility of changing the POW targets to minimize the dc offset during manual line energization, rather than solely focusing on reducing voltage transients, is considered. Nonetheless, the protection against switching surge voltages is already provided by three high-energy line surge arresters with a 1.5 pu protective level.

The POW controller applied at BC Hydro automatically switches to the manual line energization mode when the line or ringdown voltage magnitude is sufficiently low. In this mode, the POW disregards the line or ringdown voltage. It uses the source voltage and the closing targets as provided by the application engineer. However, during line autoreclose, it switches to the beat minimum when the ringdown voltage magnitude is large enough. During the failure reported in Event A, the POW closing targets from the application engineer were too close at the zero-crossings of source voltages to minimize voltage transient.

A new strategy was contemplated that involves changing these targets to minimize the dc offset current in the reactor for manual energization. The new POW closing target is selected based on the level of shunt compensation on the line. For example, in a 70 percent shunt-compensated line, the desired POW target angle is approximately 45 degrees or $\sin^{-1}(0.7)$, which corresponds to 2 milliseconds after the zero-crossing of 60 Hz source voltage on each phase.

The implementation of this corrective action strategy is in progress and has already been deployed on some of the highly shunt-compensated lines.

3) *Follow Terminal Reclosing Supervision Logic Improvements*

The autoreclose supervision logic at the follow terminal utilizes the restoration of 90 percent positive-sequence voltage as an indication of a successful autoreclose at the lead terminal. This confirmation ensures that the line is healthy and ready for autoreclose at the follow terminal without any additional delay. Although this logic had been in service for many years in both compensated and uncompensated lines, the failures in these events revealed some weaknesses in this logic. It allowed the follow terminal breaker to reclose even when the lead terminal had retripped immediately upon autoreclose.

Fig. 24 proposes an improvement in the supervision logic, utilizing all three phase voltages supplemented by the absence of negative-sequence voltage instead of relying solely on positive-sequence voltage. The enhanced logic requires all three phase voltages to be above 90 percent and the negative-sequence voltage to be below 10 percent as indicators of healthy line voltages. To ensure a secure operation, a time delay of 60 to 200 milliseconds is proposed, allowing transients from a lead terminal autoreclose to subside before the follow terminal attempts an autoreclose.

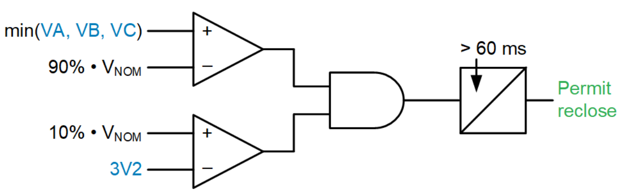

Fig. 24. Follow terminal reclosing supervision using the voltage and a coordination time delay.

The proposed supervision logic was tested using the voltage waveforms recorded by the relay at the follow terminal during Event E. Fig. 25 compares the performances of the proposed and existing logics. In the top-middle chart, which displays the line voltage magnitudes at the follow terminal, it can be observed that the lead terminal closed on the high-impedance Phase-B-to-ground fault at about 650 milliseconds. Shortly after, the positive-sequence voltage reached the 90 percent threshold, allowing the reclose to proceed when the existing logic was used during the failure event. While the follow terminal breaker was still in the process of closing, the lead terminal tripped and opened at about 700 milliseconds because of the permanent fault. Finally, it closed only after the opening of the lead terminal and thus had uncontrolled closing, as shown in the top chart displaying the terminal line currents. In contrast, the proposed logic would have prevented autoreclose from proceeding at the follow terminal due to two reasons: (a) the faulted Phase B voltage remained below the 90 percent threshold, as shown in the top-middle chart displaying the phase voltages, and (b) the negative-sequence voltage rose above the 10 percent threshold shortly after the closing of the lead terminal, as shown in the bottom-middle chart showing the negative-sequence voltage. Consequently, the input to the 60-millisecond time delay never asserted.

In Fig. 25 and Fig. 26, FL denotes the follower terminal. LD denotes the lead terminal. CL denotes close supervision logic. V3P is the min(VA, VB, VC), and PKP is the pickup threshold. PERM denotes the permission to reclose.

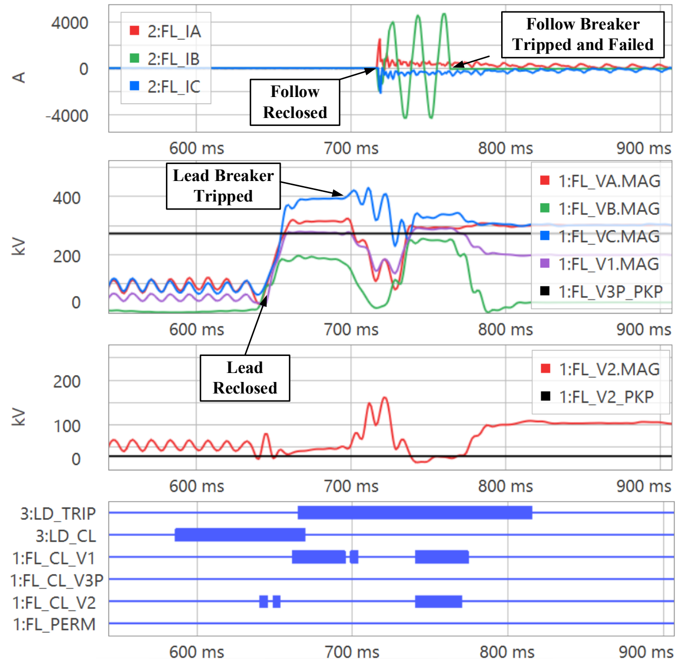

Fig. 25. Secure performance of reclose supervision logic for Event E. Analog traces from top to bottom: (1) follower breaker three-phase current, (2) follower breaker line voltage measurements and threshold, and (3) follower breaker line negative-sequence voltage measurement and threshold.

Similar tests were conducted for Event C, in which autoreclose at the lead terminal occurred on the healthy line. The proposed supervision logic correctly blocked the breaker autoreclose sequence. Fig. 26 illustrates the results. It shows that line voltage on all three phases recovered at the follow terminal, and no negative-sequence voltage was present because there was no fault. Thus, the input to the 60-millisecond timer was asserted. But the output timer was never asserted because the lead terminal tripped before the expiration of the timer, causing the voltage to drop below the threshold and preventing follow terminal autoreclose from proceeding.

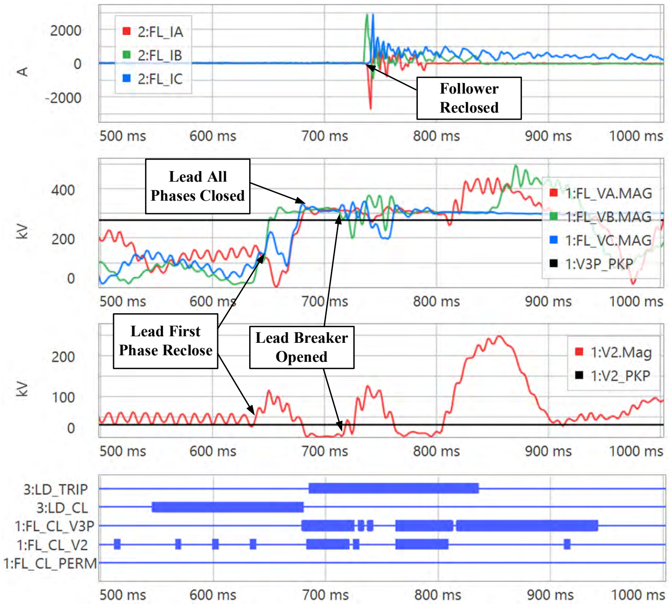

Fig. 26. Secure performance of reclose supervision logic for Event C. Analog traces from top to bottom: (1) follower breaker three-phase current, (2) follower breaker line voltage measurements and threshold, and (3) follower breaker line negative-sequence voltage measurement and threshold.

4) Zone 1 Phase Mho Transient Security Enhancement Logic

In Events B and D, the Zone 1 phase mho protection picked up transiently and contributed to the failures. The protection security is now enhanced by adding permanent half-cycle delays on all shunt-compensated lines. Instead of adding permanent delays, the logic can be improved, as shown in Fig. 27, to supervise the addition of delays with the open terminal logic. A half-cycle security delay is applied only when the line is first energized. Two cycles after line energization, Zone 1 reverts to operating without delay.

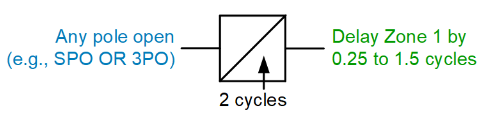

Fig. 27. Zone 1 security logic for adding a half-cycle delay during line energization.

The logic of Fig. 27 slows down Zone 1 when any phase at the local terminal is open, which may be undesirable in some applications, e.g., single-phase tripping. The challenge to protection occurs when the line is being energized following a period of de-energization from both terminals. Upon line energization, the relay's polarizing voltage angle suddenly changes when the frequency suddenly changes from the ringdown frequency to 60 Hz, the power source frequency. When the line is de-energized from both terminals, the line VTs measure the ringdown voltage at an off-nominal frequency. A ringdown voltage detection logic was proposed earlier [15]. It uses frequency supervision to improve the security of sensitive and fast shunt reactor protection. A similar approach can be used to delay Zone 1; the associated logic is shown in Fig. 28. If the frequency measurement is not healthy (NOT FREQOK) or if the measured frequency (FREQ) is significantly off nominal (e.g., a 2 percent difference from the nominal frequency, NFREQ) for a few cycles (e.g., 3 to 6 cycles), then a short delay is added to Zone 1.

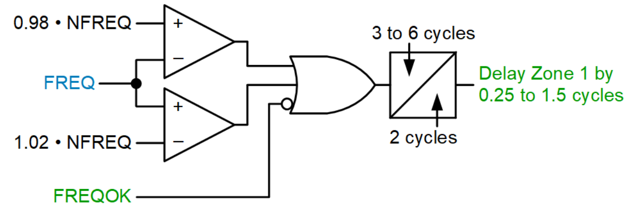

Fig. 28. Zone 1 delay using frequency supervision.

The frequency supervision logic, shown in Fig. 28, with a pickup time of 6 cycles was implemented, and Event D was played back through the relay with the results illustrated in Fig. 29. FREQOK drops out after the line is de-energized from both terminals and the relay starts measuring the ringdown voltages. After 6 cycles, the additional time delay is added to Zone 1 and the relay remains secure.

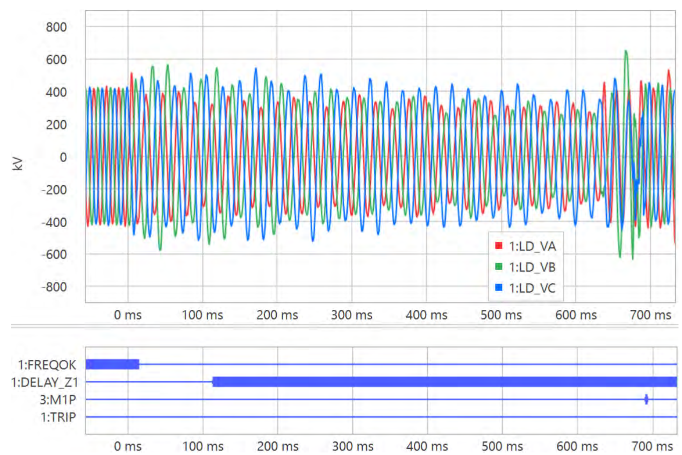

Fig. 29. Secure performance of frequency supervision for Event D.

Another option that was considered to secure Zone 1 phase mho was the use of overcurrent supervision (i.e., a fault detector) to add security. The overcurrent pickup may be set to remain secure for the compensated charging current of the line, for example, with one reactor in service. When the line carries sufficient load or fault current, missing zero-crossings are not a concern. For dependability, the overcurrent supervision may be set to pick up at a value less than half the current for a fault at the zone boundary. An alternative is to set the overcurrent element above the maximum shunt reactor current dc offset. The dc offset may be higher during possible line overvoltage and frequency differences during reclosing, which may be considered to help ensure security of the overcurrent supervision.

C. Long-Term

The IEEE application guide "IEEE Std C37.010-2016, IEEE Application Guide for AC High-Voltage Circuit Breakers > 1000 Vac Rated on a Symmetrical Current Basis" [17] discusses the more efficient surge control using pre-insertion resistors than other methods like POW control. The long-term plan of corrective measures, still under consideration, focuses on reducing the dc offset current by reintroducing the pre-insertion resistor. It emerged after examining the line energization methodologies employed by three other utilities, Hydro Quebec [18], Manitoba Hydro, and Bonneville Power Administration (BPA), and aligns with their methodology. All three have extensive operational experience with lines where more than 50 percent of compensation is utilized.

Hydro Quebec [18] and Manitoba Hydro operate 765 kV and 400 kV lines, respectively, that are highly shunt-compensated. While they adopted POW-controlled closing in other applications, they did not adopt it for switching high shunt-compensated lines due to concerns about breaker failures. Instead, they continue to employ pre-insertion resistors for line energization and de-energization.

BPA operates 500 kV circuits with high shunt compensation. Like BC Hydro, BPA has two forms of 500 kV line constructions: 2.0 pu and 1.7 pu, as discussed in Section 2. On the 1.7 pu lines, BPA uses pre-insertion resistors for line energization and de-energization. Additionally, it applies POW-controlled energization but tunes the closing targets during manual energization to minimize dc offset. POW-controlled closing is used on the 2.0 pu line, again with targets tuned to minimize dc offset current. During POW-controlled autoreclosing, BPA uses only the bus voltage with fixed targets corresponding to a shunt reactor [19], which is intended to minimize current dc offset.[13] Although the design does not require pre-insertion resistors on the 2.0 pu line, many of the breakers are equipped with pre-insertion resistors because one of the two circuit breaker suppliers offers them as a standard option.

BC Hydro has more than 20 highly shunt-compensated lines; therefore, the plan will require retrofitting a large number of relatively new SF_6 breakers. The original suppliers of these breakers are being engaged to explore multiple retrofit options, associated costs, and the amount of work required at stations, which may involve circuit outages for retrofitting or redeploying the breakers. The plan will require a significant capital investment and take several years to implement fully. Thus, midterm countermeasures are essential to mitigate the risk while the long-term plan is finalized and executed.

VI. Conclusion

This paper analyzed five catastrophic breaker failure events that posed significant safety risks. All failures occurred on highly shunt-compensated lines, with four utilizing POW-controlled energization. The root cause of these failures was missing zero-crossings in the line energization currents when the breakers were attempting to interrupt them.

One of the failures occurred during manual line energization. The POW control performed almost flawlessly, effectively controlling switching surge voltages as intended. However, it inadvertently introduced a dc offset with missing zero-crossings in the line current. An incorrect protection setting, leading to the line trip upon energization, caused the breaker to fail due to the missing zero-crossings.

Four additional failures were observed during line autoreclose. These incidents revealed a weakness in the autoreclose supervision logic, leading to uncontrolled closing at the follow terminals with missing zero-crossings in the line current. One correct and three incorrect protection trips contributed to the failures. The protective relay manufacturer attributed two of the incorrect operations to wide pole scatter during line energization, which was a result of the POW controllers not being able to identify beat minimums.

Applying POW-controlled switching in highly shunt-compensated transmission lines poses a significant challenge, as it is highly likely to introduce dc offset and missing zero-crossings in the line energization currents. Manual line energization is a routine operational event. During the lightning season, line autoreclose is also common at BC Hydro, where the transmission system lacks shield wires. Consequently, a protection operation during one of these everyday line energization events will likely cause a breaker failure. Although protection operations during line energizations are not everyday occurrences, they cannot be eliminated and should be expected.

To ensure the reliable and safe operation of highly shunt-compensated lines, addressing the vulnerability associated with missing current zero-crossings is crucial. Considering other utility operational experiences, reintroducing pre-insertion resistors is being contemplated as a long-term countermeasure. However, this plan will necessitate significant capital funding, long-term planning, and implementation.

In the short- and midterm, making incremental changes to the line protection systems will help mitigate undesired operations and reduce the probability of such failures. For manual line energization, lowering the shunt-compensation level to below 50 percent can mitigate events with missing current zero-crossings and minimize the risk of exposing breakers to them during trips. Proposed improvements in the autoreclose supervision logic will also reduce the risk of uncontrolled closing and minimize the exposure of breakers to missing current zero-crossings at the follow terminals.

The primary objective of this paper is to raise industry awareness of the risk faced by station personnel working in proximity to highly shunt-compensated line terminals that are energized using POW-controlled energization. Transmission line energizations are common occurrences, and the corrective measures discussed will reduce exposure by minimizing protection trips and by eliminating missing zero-crossings during manual energizations.

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VIII. Biographies

Mukesh Nagpal is a senior associate technical consultant at Burns & McDonnell, an IEEE Fellow, and a distinguished lecturer of the IEEE Power & Energy Society. He is also an adjunct professor at the University of British Columbia and a professional engineer in the province of British Columbia. Furthermore, he is recognized as a Fellow of Engineers Canada. With over 35 years of experience in electric utility research and power system protection, Mukesh has made notable contributions to the economic, safe, and reliable integration of renewables into the electric grid. He has published approximately 50 technical papers, showcasing his expertise in this field.

Kenan Hadzimahovic is an engineering team lead at BC Hydro with over 13 years of experience in power system protection. Kenan received his BS and MEng degree in electrical engineering from the University of British Columbia. Kenan's work at BC Hydro is focused on planning and providing business solutions for system upgrade projects, load and generator interconnections, and maintenance projects. He is a registered professional engineer in the province of British Columbia.

Tyler Scott is a specialist engineer at BC Hydro with over 20 years of experience in power system protection. Tyler received his BSc degree in electrical engineering from the University of Alberta in 2002. He is a registered professional engineer in the province of British Columbia. Tyler's work at BC Hydro has focused on a variety of protection systems, including high-voltage line protection, large distribution substation protection, as well as regulatory compliance and high-voltage customer and generation interconnection.

Tony Jiao has a BSc and MSc in Electrical Engineering from Zhejiang University, Hangzhou, China. He joined BC Hydro in 2004 and is presently a principal engineer in the protection and control planning department.

Ralph Barone has over 30 years of experience in power system protection and control. Ralph received his BASc degree in electrical engineering from the University of British Columbia in 1988. He worked for BC Hydro from 1988 to 2019 in HVdc, telecom, and protection and control before becoming a consultant. Ralph is a senior member of the IEEE and a registered professional engineer in the province of British Columbia.

Fernando Calero is a principal engineer at Schweitzer Engineering Laboratories, Inc. (SEL) in the research and development (R&D) division. For 20 years, he was an application engineer in the SEL international organization. His responsibilities included the application, training, and support of SEL products. In 2020, he transferred to the R&D division and is working on projects related to renewable sources, protection, and control. He holds eight patents and has written technical papers on protective relaying, remedial action schemes, and other protection and control applications. He is a registered PE in the state of Florida.

Ritwik Chowdhury received his BS degree in engineering from the University of British Columbia and his MS degree in engineering from the University of Toronto. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2012, where he is presently a senior engineer in research and development. Ritwik holds over 10 patents and has coauthored over 25 technical papers. He was recognized as an exceptional reviewer for *IEEE Transactions on Power Delivery* for three years. He is the chair of the Protection and Control Practices Subcommittee (I-SC) of the IEEE Power System Relaying and Control (PSRC) Committee, the chair of two IEEE Standards Working Groups, and the recipient of the 2021 PSRC Outstanding Young Engineer Award. Ritwik is a senior member of IEEE, a member of CIGRE, and a registered professional engineer in the province of Ontario.

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