BC Hydro Protection Interconnection Practices for Sources with Inverter or Converter Interface

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Abstract: *Power electronic converter or invertor interfaces, connecting stationary or rotating energy sources to the electric grid, are fast switching devices. The designers of these interfaces, therefore, have great flexibility under program control to manage the current output of the source particularly during short circuit conditions. Unlike a synchronous generator whose current output immediately after inception of a short circuit is uncontrolled, high magnitude and has universal characteristic, the current from a converter or an inverter interfaced source is controlled, and is generally low in magnitude. The short circuit current characteristic is completely dependent upon a specific, and often proprietary, control system that is designed to protect the interfacing power electronics and to meet utility grid code requirements. As a consequence, the reliability of conventional protection schemes, designed for conventional rotating machine sources, can be at risk when they operate solely on the current contribution from the interfaced sources but do not take into account the controlled nature of their short circuit currents. Using real life examples of short circuit currents on lines supplied by sources having converter or inverter interfaces, this paper illustrates the reliability risk to conventional line protection schemes, in particular to those which use negative sequence quantities for detection of unbalanced faults. This paper discusses the protection schemes, adopted by BC Hydro for lines interconnecting sources with converter or invertor interfaces. Their application for ground faults is independent of the control system design as long as the interfaced source is connected to the grid via a transformer which is a source of zero sequence current.*

Key Words*: Generator Interconnection, Transmission Line Protection, Negative Sequence Polarization, Wind Turbine Generator, STATCOM, Battery Storage, Converter-Inverter Interface*

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1. Introduction

Rapid technological advancements and reduction in cost are contributing to high penetration of active and dynamic reactive power sources with electronic converter or inverter interfaces to the electric grid. In this paper, these sources are (for convenience) referred to as “interfaced sources”. Their increasing penetration is creating new challenges for protection engineers because the short circuit current characteristics of these interfaced sources are very different from traditional rotating synchronous sources. Current from a synchronous source or generator, immediately after a short circuit and within timeframe of protection operation, is uncontrolled and can be universally defined by electrical parameters of the source and short circuit path impedance. However, the short circuit current of the interfaced sources is highly controlled and managed by using fast switching of power electronics dependent upon manufacturer specific and often propriety control system design. Their key design objectives include meeting utility grid code [1] and limiting the magnitude of current within the thermal withstand capability of the power electronics during short circuits. Thus, the interfaced sources have non-universal and complex short circuit current characteristics. In addition with the exception of only one grid code, all other existing grid codes to connect interfaced sources to the electric grid primarily focus on positive sequence reactive current injection in response to disturbances involving voltage depressions. In the absence of any negative sequence requirement from interconnecting utilities, the interface control systems are often designed to suppress negative sequence currents.

Technical literature has widely recognized the dissimilar nature between short circuit currents from traditional synchronous and interfaced sources [2-7]. It has naturally then raised concerns related to reliability of the conventional protection schemes when operating on short current solely supplied by from the generating stations having sources with power electronic interfaces [8-10]. The intent of this paper is to discuss the measures in conventional line protection schemes to counter for low-magnitude or uncertainties in the characteristic of the short circuit current, in particular lack of negative sequence current, from the interfaced sources during ground faults. This paper uses the following examples of recorded short circuit currents and voltages on the lines, supplied from the interfaced sources during actual faults:

Example 1: A single phase-to-ground fault evolving to a double phase-to-ground fault supplied by Type 3 wind turbine sources

Example 2: A single phase-to-ground fault where fault current contribution from Static Synchronous Condenser or STATCOM source contributed to undesirable line protection operation for an out-of-zone fault

Example 3: A 25 kV double line to ground fault supplied by battery inverter source

For space reasons, only three fault examples are described but other fault records also confirm the findings.

The remainder of the paper is organized into seven more sections. Section 2 uses the often quoted German Grid Code as an example to illustrate influence of the utility interconnection requirements on design of the interfaced sources and thereby their short circuit current outputs. Section 3 provides a brief overview of principle used in the conventional negative and zero voltage polarized directional schemes. This overview is provided to contrast with the focus of the discussion herein, which is on performances of these schemes on the fault currents supplied by interfaced sources. Sections from 4 to 6 present three examples mentioned above. Section 7 discusses BC Hydro strategy to achieve reliable protection for all type, phase and ground, faults on the lines connecting power electronic-based sources. Finally, conclusions are outlined in Section 8.

2. Grid Code

In this section, performance requirements for renewable energy sources [11] from one of the major utilities in Germany, E.ON (transmission assets now acquired by TenneT Arnheim), are used to illustrate how these codes are impacting designs of interfaced sources, and consequently their behavior and protection responses during short circuits.

Low Voltage Ride Through Requirement:
Figure 1 shows low voltage ride through requirement imposed by E.ON for the interfaced generators wanting to connect to its transmission system. Other utilities and reliability regulators, have low voltage ride through requirements which are a variation of the E.ON code. The generator now must remain connected when the voltage depression from an external fault is within the low voltage ride through requirement of the applicable grid code. Because of this requirement, the short circuit current characteristics of the interfaced sources have become relevant to the line protection security. An undesirable line protection operation during an external short circuit will disconnect the generator and defeat the purpose of the grid code.

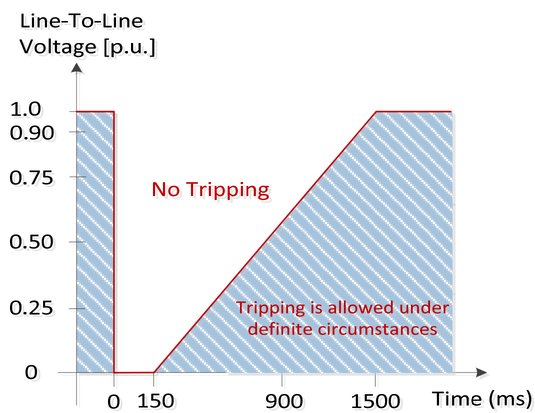


Figure 1: Low voltage ride through requirement by E.ON.

Dynamic Reactive Support Requirement:
Besides the low voltage ride through requirement, Figure 2 describes the E.ON requirement of mandatory dynamic voltage support during short term voltage drops or increases by interfaced sources.

In case of voltage depressions, the unit is required to inject positive sequence capacitive currents, while during overvoltages it is required to inject positive sequence inductive currents, irrespective of fault type. Except for one recently introduced new grid code in Germany [12], the E.ON. code as well as all of the others have no requirement concerning the negative sequence current injection. Hence, the manufacturer usually designs the control system to supress negative sequence current. Absence of negative sequence current during unbalance faults, as a consequence, may threaten protection dependability i.e. its ability to operate and isolate the fault line for unbalance faults. Power electronic sources are typically not grounded so no zero sequence current injection requirements exist.

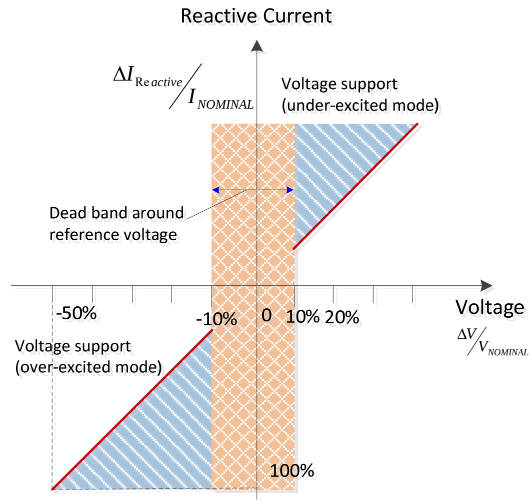


Figure 2: Dynamic reactive current requirements during voltage excursions by E.ON.

3. Negative and Zero Sequence Voltage Polarized Direction Relays

This section provides a brief overview of principle used in conventional negative and zero sequence voltage polarized directional relaying before describing the impact of interfaced sources on the scheme in the subsequent three sections.

Figure 3 shows is an effectively grounded and networked system that has two lines connected in series. These lines tie two systems sourced by traditional synchronous generators. A negative or zero sequence voltage polarized directional relay is shown at Breaker 2 location. This figure has three parts: (a) the top part is a simplified one-line diagram with a solid ground fault in the forward direction of the relay at Breaker 2 location, (b) negative or zero sequence reactance diagram of the network and (c) 60-Hz phasor diagram illustrating the relationships between negative or zero sequence polarizing voltage and corresponding sequence current for the forward fault seen by the relay at Breaker 2 location. Neglecting network resistance for illustrative simplicity, and assuming conventional counter clockwise rotation of the phasors, the sequence current leads the corresponding polarizing voltage for the forward fault seen by the relay. Likewise Figure 4 is identical to Figure 3, except the fault direction is reversed for the relay at Breaker 2 location. As a consequence, relationships between negative or zero sequence polarizing voltage and its corresponding sequence current are also reversed i.e. the current now lags the voltage for the reverse fault.

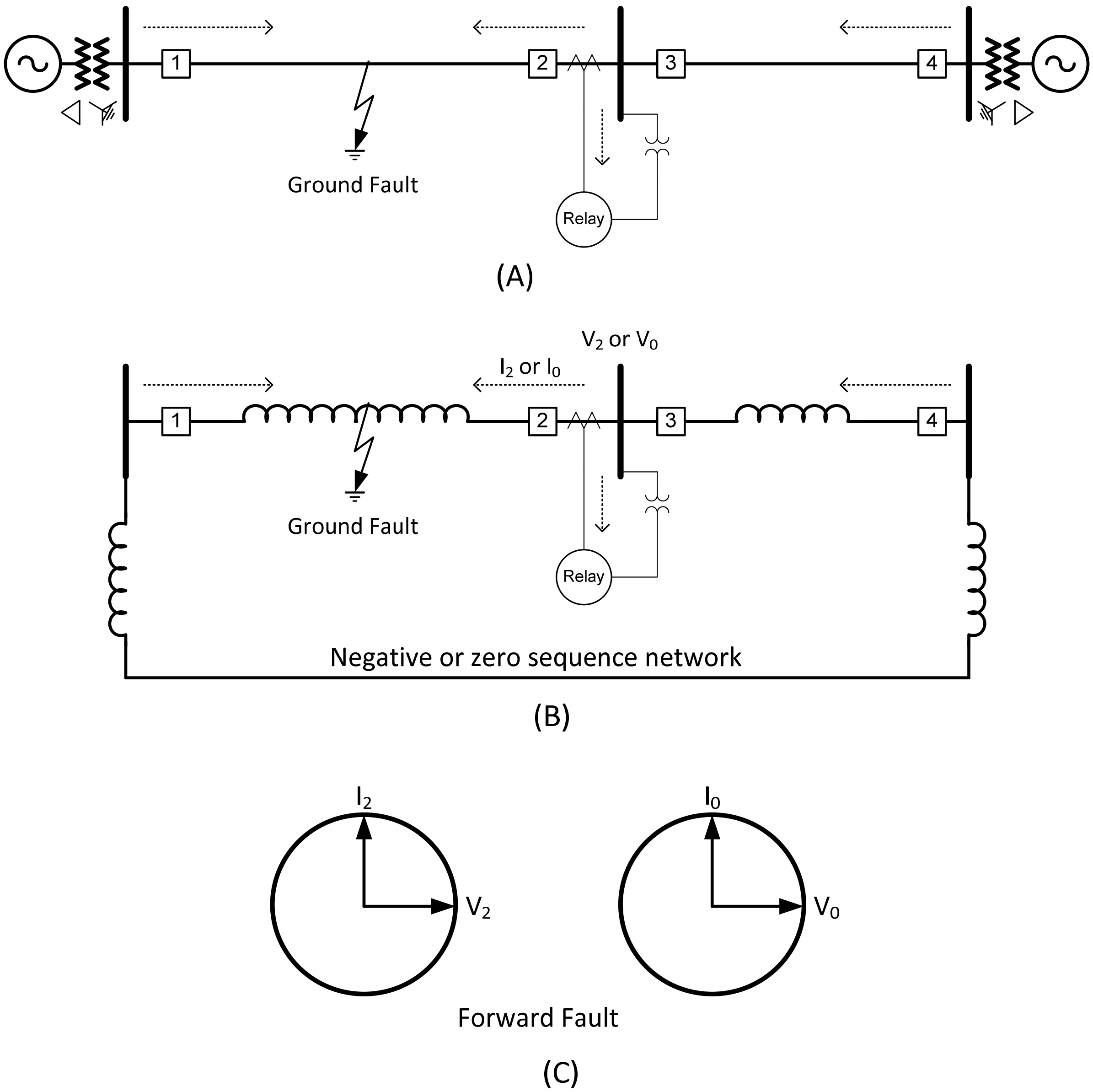


Figure 3: Negative or zero sequence polarized voltage relationship to its corresponding sequence current for a forward fault with conventional sources at both line terminals.

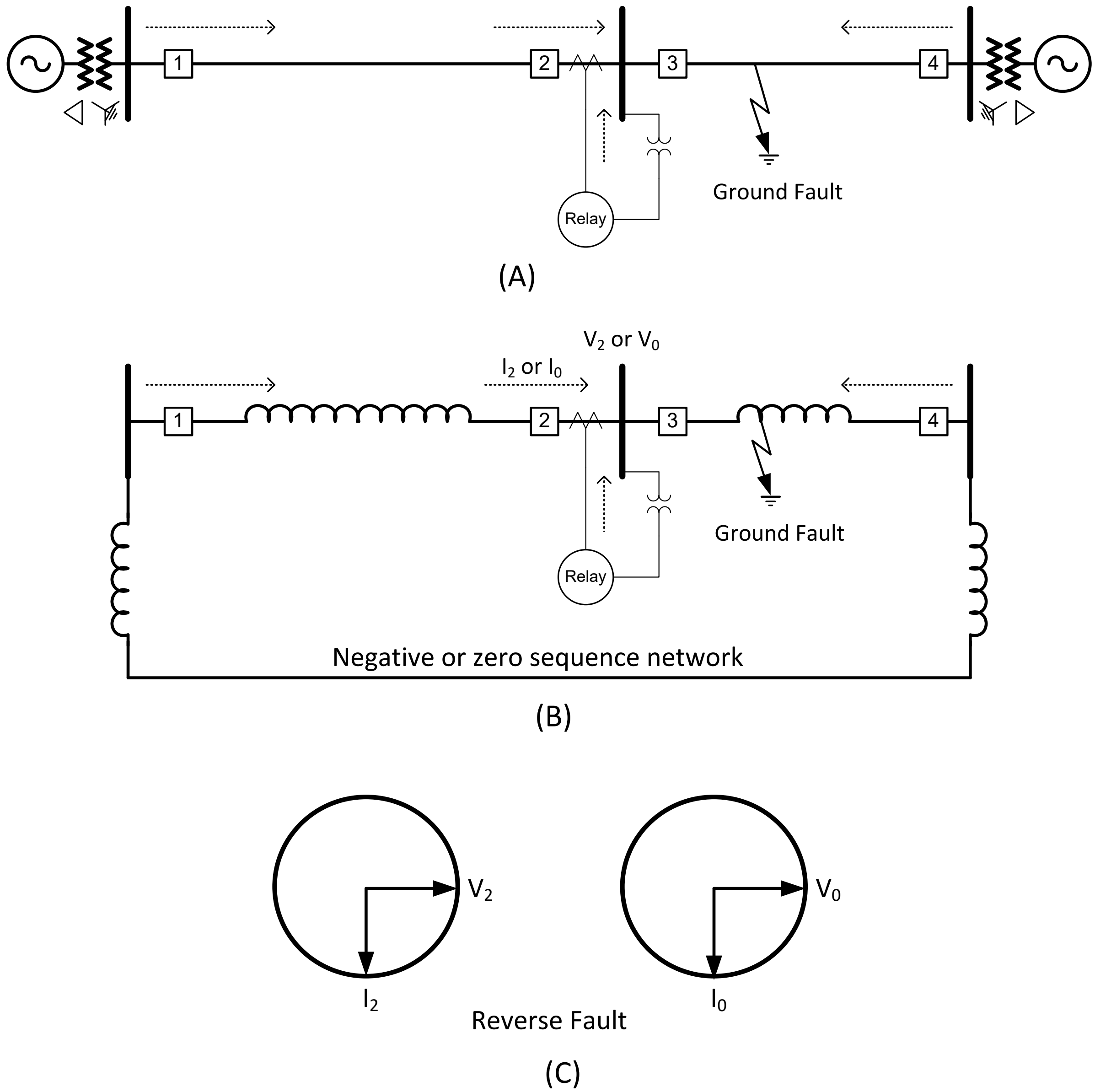


Figure 4: Negative or zero sequence polarized voltage relationship to its corresponding sequence current for a reverse fault with conventional sources at both line terminals.

4. Example 1 – Type 3 Wind Turbine Generator

Several type 3 wind turbine generator stators are directly connected to the grid. The generator rotors are built with three-phase windings which receive their excitations from a power converter also connected to the grid. Since the converter system is only interfaced to the rotor circuit and the stator is directly connected to the grid, the power converter contributes only partial i.e. 30-40% of the generator rated power. The laminated rotor with short time flux time constant and power electronic excitation system provides fast reactive power control and voltage regulation.

System Description:

Figure 5 shows the 230 kV transmission system between Gordon M. Shrum (GMS) and Tumbler Ridge (TLR) substations of BC Hydro.

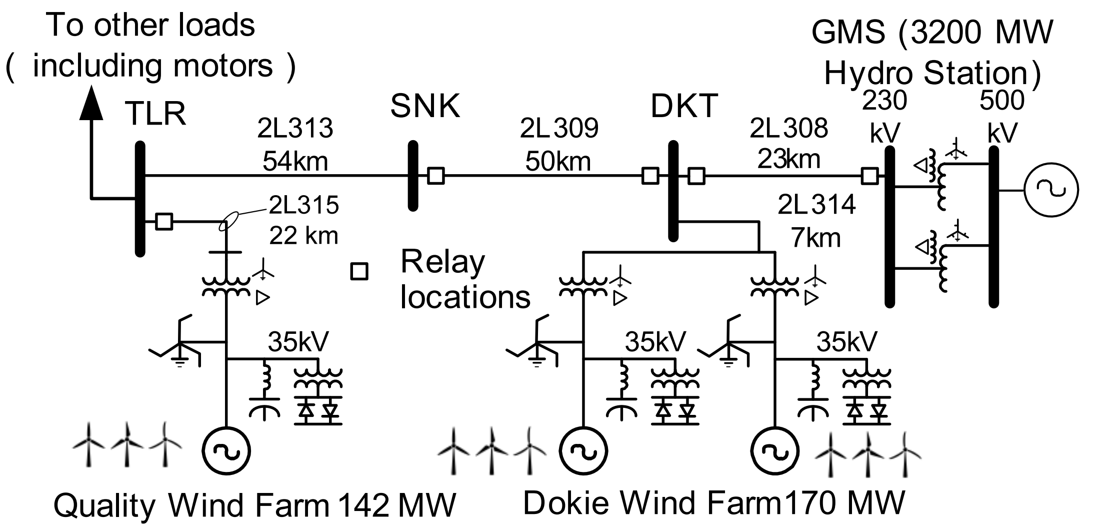


Figure 5: 230 kV transmission one-line between GMS and Tumbler Ridge (TLR) substations of BC Hydro.

GMS is a large hydro generating station. TLR supplies power to transmission and distribution customers. TLR is also a point-of-interconnection for the nonutility 142 MW Type 3 wind generating station (Quality Wind Farm). Dokie Terminal (DKT) is a switching station that interconnects another nonutility 170 MW Type 3 wind generating station (Dokie Wind Farm). Both generating stations were integrated into the BC grid via wye-grounded/delta transformers with wye-grounded windings on the 230 kV. This transformer configuration not only provides effective grounding to the transmission system but also acts as source of zero sequence current for ground faults on the transmission system. In protection literature, these transformers are also referred to as zero sequence current sources.

5th August, 2014 Evolving Ground Fault on 2L308:

On 5th August, 2014, 2L308 experienced a Phase B-to-ground fault about 13.5 km from GMS. After about three-cycles, it evolved into Phase B-to-C-ground fault. Figure 6 shows "filtered" records captured by GMS 2L308 relay looking into the fault. "Filtered" refers to analog signals that were preprocessed by the 60-Hz band-pass digital filter in the relay. In this figure: the top analog traces are phase currents; top middle analog traces are magnitudes of the three sequence currents; bottom middle digital trace is status of the negative sequence forward directional element (32GF) element in the multifunction microprocessor-based relay; and the bottom phasor diagrams are phase angles of each sequence current relative to its corresponding sequence voltage at about two cycles into fault (see cursor indicating "phasor time reference" on the figure). In all phasor diagrams throughout this paper, the positive sequence voltage is used as the reference, time reference of the phasor diagrams is also illustrated by the cursor on the analog traces and phasors rotate anti-clockwise. Zero and negative sequence current contributions were substantial from the strong integrated system. Their phase angles were leading respective sequence voltages by about 90º as expected in the conventional system with inductive path to a forward short circuit fault. This phase angle remained consistent even after the fault transitions from Phase B-to-ground to Phase B-to-C-to-ground and did not change until after the fault was cleared. The negative sequence forward directional element asserted shortly after the fault inception and remained asserted until the fault was cleared.

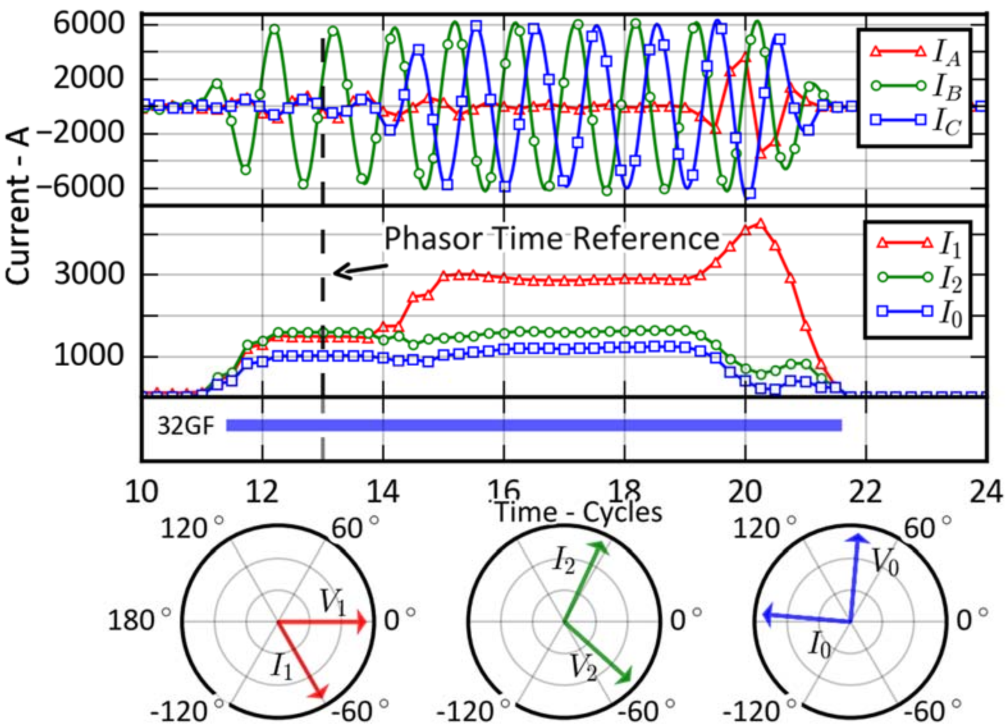


Figure 6: GMS 2L308 relay records for an evolving forward ground fault contributed by conventional source.

Figure 7 shows records from the DKT 2L308 relay for the forward fault current by the wind turbine generation. Zero sequence current magnitude was more than 600 A and led the corresponding sequence voltage by about 90° while the negative sequence current was less than 90 A and was almost *anti-phase* with the corresponding sequence voltage. The negative sequence forward directional element asserted transiently during the event.

Likewise, Figure 8 shows records from the TLR 2L315 relay for the reverse fault i.e. source of the reverse fault current was Type 3 wind generating station. Initially zero sequence current was 90 A and it increased to about 140 A as the fault evolved from single line- to double-line-to-ground fault. The phase angle of zero sequence current was consistently lagged by about 90° from the corresponding sequence voltage. Negative sequence current was less than 40 A and was almost *in-phase* with the corresponding sequence voltage. Though phase angles are shown at about two cycles after the ground fault inception, they maintained similar relation for the duration of the fault. In this figure, the digital trace is the status of the negative sequence reverse directional element (32GR) which picked up only transiently during entire event.

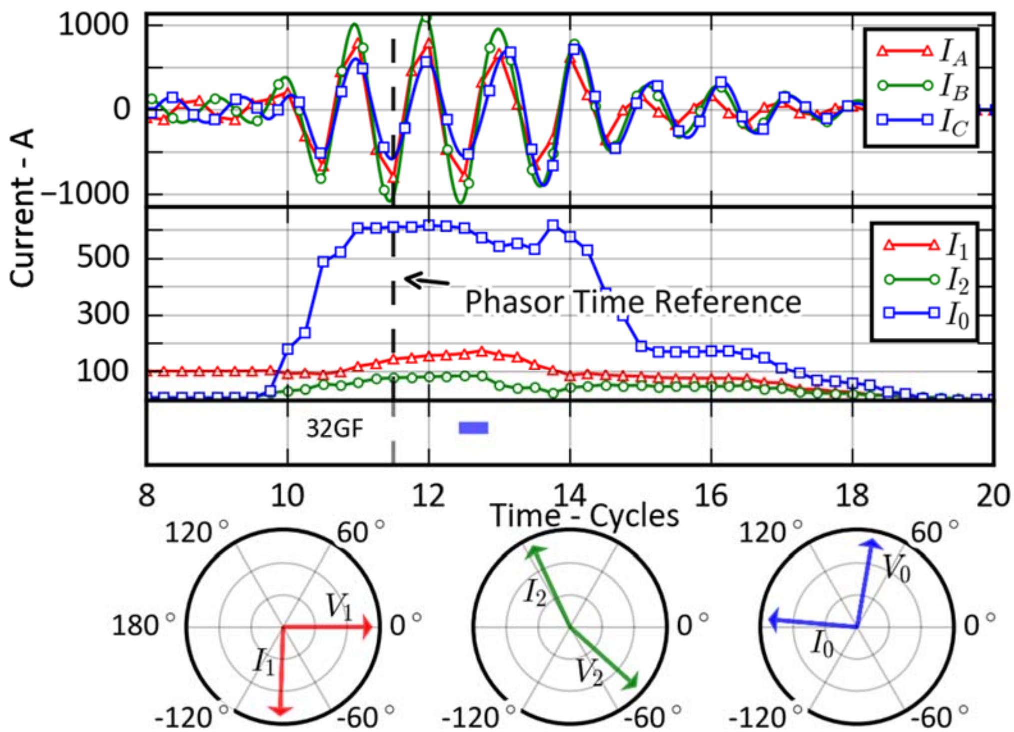


Figure 7: DKT 2L308 relay records for an evolving forward ground fault contributed by Type 3 wind turbine generator.

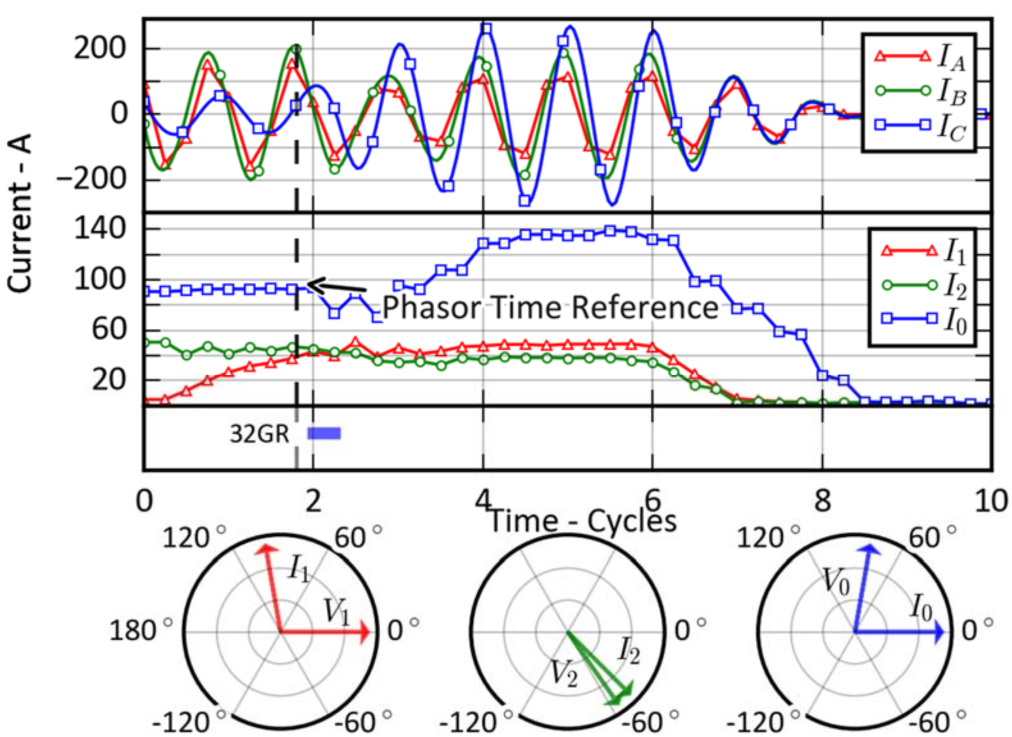


Figure 8: TLR 2L315 relay records for an evolving reverse ground fault contributed by Type 3 wind turbine generator.

Lessons Learned:
Short circuit current analysis confirmed that the negative sequence current phase angle relationship to negative sequence voltage from a Type 3 wind turbine generator is unlike that of conventional sources and is not readily known. Therefore, conventional negative sequence current based scheme can't provide reliable protection against ground faults in situations with high penetration of converter interface sources influencing short circuit currents. However, if these generators are connected through a transformer that is a source of zero sequence current, then the ground protection can be achieved using zero sequence current. The protection will be predominantly independent of type of wind turbine generator or its associated control algorithm because the interconnecting transformer, not wind turbine generator, is the source of zero sequence current in that case.

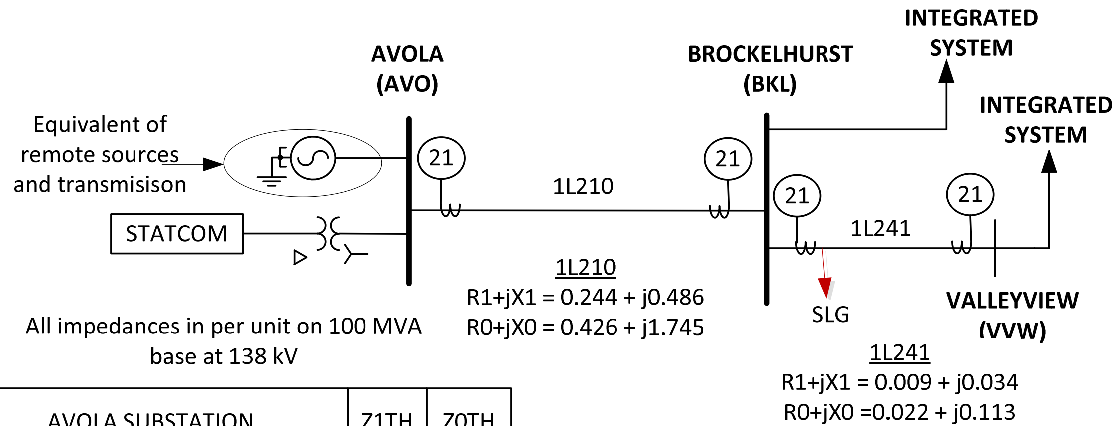
5. Example 2 – STATCOM Source

STATCOM sources interface with the grid via a full-scale power converter. Their output is fully defined by the power converter control instead of natural response of the source to sudden changes in power system. Since there are no requirements to inject negative sequence currents by majority of the existing grid codes, their control systems are typically programmed to supply symmetrical current for all symmetrical and unsymmetrical faults. Although the control system varies significantly among the suppliers, the present day full-scale power converter sources can essentially be viewed as having very high negative and zero sequence impedances. The magnitude and phase angle of the positive sequence current during faults are again optimized by the suppliers to suit their own power converter operations [2, 6] but typically the magnitude limited is in the range of 1.0 to 2.0 p.u.

Following is a discussion of an undesirable line protection operation during a ground fault caused by a STATCOM whose control is designed to respond to voltage depressions similar to the low voltage ride through requirements for power electronic-based generators.

This section compares the currents seen by two 138 kV transmission lines, referred to as upstream and downstream lines, feeding a single phase-to-ground fault. The downstream line had a stiff synchronous source from the integrated BC Hydro system whereas the upstream line had a relatively weak source and large STATCOM. The upstream line experienced an undesirable protection operation and the fault records are used to identify the cause of this operation.

System Description:
Figure 9 shows a simplified one-line diagram of the North Thompson 138 kV Regional Transmission System in BC Hydro. Brockelhurst (BKL) is a transmission switching station connected to the integrated BC Hydro grid. Upstream of BKL, 1L210 is a 195 km long transmission line to Avola (AVO) which connects to a transmission system interconnecting several small sources of generation. There are several transmission tap-connected pumping loads along the transmission line, not shown on the one-line diagram, from BKL to AVO. A pair of STATCOMs, continuous rating of each ±12 MVAr with combined temporary overload rating ±48 (2×24) MVAr, is installed at AVO for dynamic reactive support during voltage depressions from transmission faults. BKL also has a similar single STATCOM but it was disconnected during this incident and thus not shown. Thevenin impedances of synchronous sources (ignoring STATCOM contribution) behind BKL 1L241 and AVO 1L210 terminals are listed in tables below the figure. Positive sequence source synchronous strength behind BKL is about ten times stronger than behind AVO. Zero sequence source strength at AVO is comparable to BKL largely because STATCOM transformers are 138 kV wye-grounded and delta on low-voltage reducing the zero sequence impedance at that station.



AVOLA SUBSTATION	Z1TH	Z0TH
Thevenin Equivalent Source impedance with STATCOM transformers, but without STATCOM positive or negative seq. contribution and without 1L210	1.55	0.271

BROCKELHURST SUBSTATION	Z1TH	Z0TH
AVOLA TRANSFORMERS IN-SERVICE	0.136	0.260

Figure 9: Simplified BC Hydro North Thompson regional 138 kV transmission one-line diagram.

<u>30th June, 2015 Ground Fault on 1L241:</u>

On 30th June, 2015, 1L241 experienced a Phase C-to-ground fault close to the BKL substation. During the fault, instantaneous Zone 1 ground quadrilateral distance protection (21G) operated correctly at BKL 1L241 but incorrectly at AVO 1L210. Because of AVO 1L210 over tripping on an external line fault, the entire North Thompson regional system lost the supply. To illustrate the cause of over tripping, the fault currents seen by the two line protection systems are analyzed and compared with those obtained from the system short circuit model that did not include full-scale converter sources (STATCOM) at AVO.

Similar to figures in Section 4, Figure 10 shows "filtered" records captured by BKL 1L241 relay looking into the fault, except digital traces are statuses of Zone 1 ground quadrilateral distance (Z1G) and trip (TRIP) elements. In Figure 10, phase angle of each sequence current relative to its corresponding sequence voltage is at about 1.5 cycle into the fault. Because the BKL substation was connected to the strong BC Hydro system, the ground fault current was about 2000 A and matched closely with the fault current obtained from the short circuit model. Again as anticipated for the conventional system, the phase angles of the negative and zero sequence currents were leading the respective sequence voltages by 90º throughout fault event. Zone 1 ground distance element picked up shortly after fault initiation and tripped correctly.

Figure 11 shows relay records for the same fault from the AVO 1L210 protection system which operated undesirably. Using Thevenin impedances of the synchronous sources (not taking into account the STATCOM) at AVO, the maximum rms value of the fault current was expected to be about 200 A but the actual maximum fault current recorded was about 240 A. The positive sequence current was not steady and reached about 130 A which was considerably higher than expected 50 A from the short circuit model. This higher current was due to reactive current injection from the STATCOM trying to maintain the voltage at AVO. The negative sequence current had a varying magnitude with the maximum value close to 55 A provided by the model. The zero sequence current remained steady at 100 A throughout the event and matched closely with the model because of wye-grounded delta windings of STATCOM and the other upstream transformers. Unlike BKL, the phase angle of the negative sequence current relative to the respective sequence voltage was varying. At about 1.5 cycles into the fault, negative sequence current was *anti-phase* (180º out of phase) with respective sequence voltage. However, the zero sequence current consistently led the corresponding voltage around 90º during the entire fault event i.e. similar to BKL.

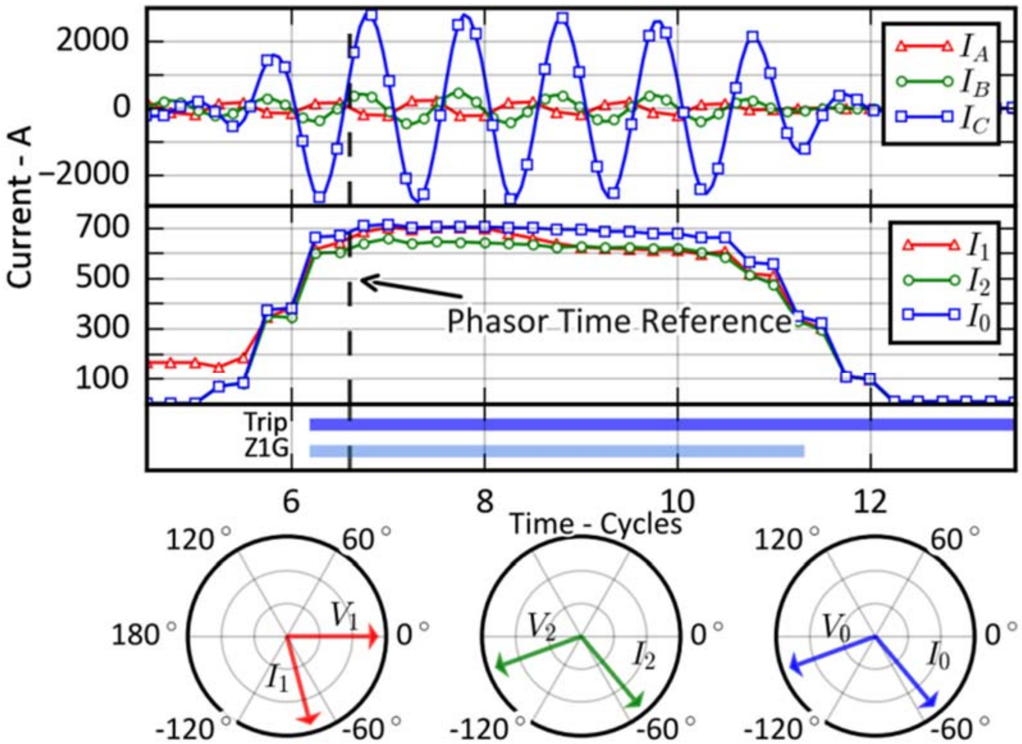


Figure 10: BKL 1L241 relay records for a forward ground fault contributed by conventional generator source.

1L210 Protection Misoperation Analysis:

The reactance blinder of the ground quadrilateral distance element applied was polarized with negative sequence current. The line impedance is 5.18 secondary ohms (104 primary ohms) and the 21G reactive reach was set to 3.8 secondary ohms i.e. the element overreached and operated beyond 125% of relay reach. Using the four samples per cycles phasor data extracted from the event captured by AVO 1L210 relay and its reactive reach characteristic [13] as described by the equation below, the ground quadrilateral distance element response was simulated for Phase C-to-ground fault.

$$X_{CG} = \frac{Imag(V_C \times I_P^*)}{Imag(Z_1 ang \times (I_C + k0 \times I_0) \times I_P^*)} \qquad (1)$$

In Equation 1 above, X_{CG} is the calculated reactance, V_c is Phase C-to-ground voltage, I_c is Phase C line current, I_0 is zero sequence line current, I_P is either zero or negative sequence polarizing current, Z_1ang is positive sequence line angle and k0 is zero sequence current compensating factor. Using negative and zero sequence currents as the polarizing quantities, Figure 12 illustrates the simulated responses of the ground reactance element for the fault duration. Shortly after, i.e. one cycle of the fault inception, the reach calculations from the negative sequence polarized relay transiently dropped below the threshold and caused the protection misoperation. During the fault, response of this element was somewhat unsteady since the negative sequence current was less predictable. The reach from zero sequence current relay was steady and remained above Zone 1 threshold before the circuit breaker started to open.

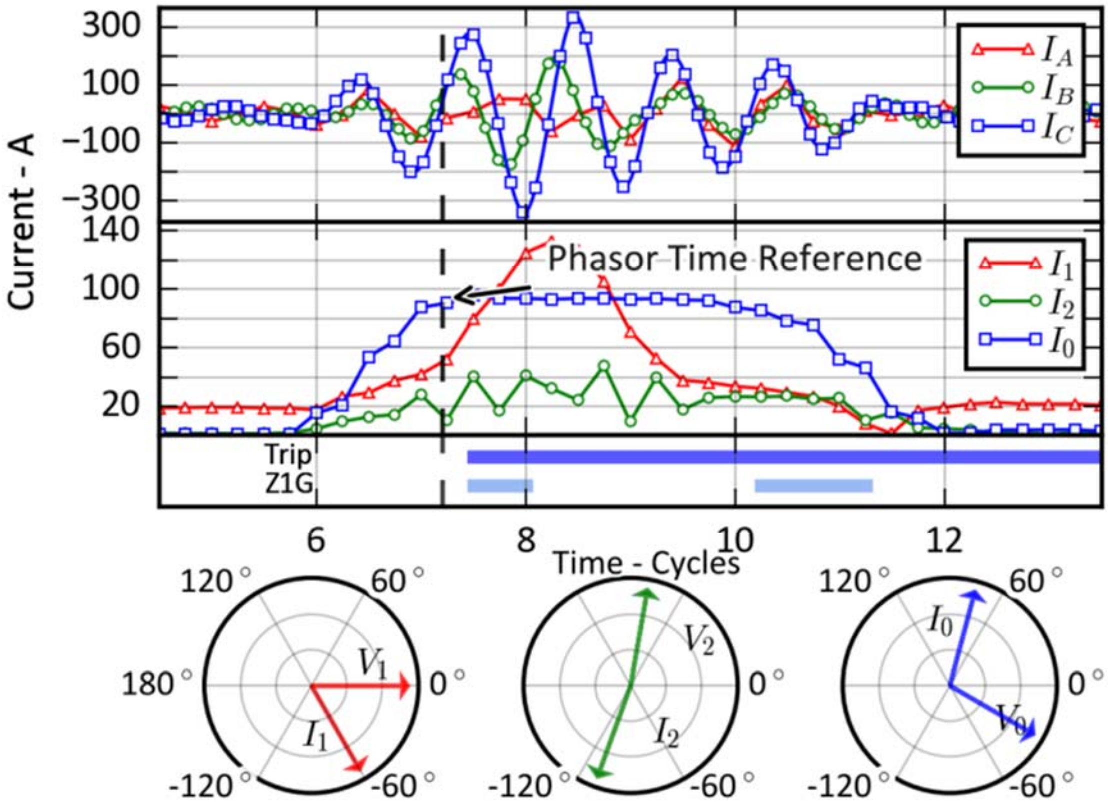


Figure 11: AVO 1L210 relay records for a forward ground fault contributed by weak conventional source system and STATCOM.

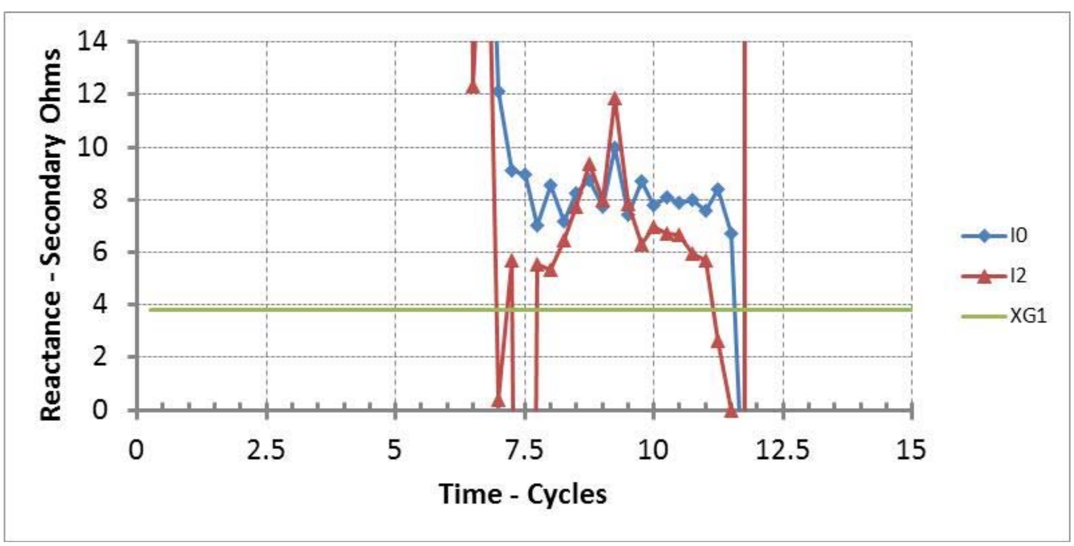


Figure 12: Simulated responses of zero (I0) and negative (I2) sequence current polarized ground quadrilateral distance relays.

The misoperation of AVO 1L210 ground quadrilateral distance relay was attributed to the STATCOM control which was attempting to raise and balance the depressed 138 kV voltage on the faulted phase at AVO by injecting reactive current behind relay during the ground fault. The negative sequence impedance behind the relay at the AVO bus was high from the weak synchronous source. So while STATCOM was attempting to raise and balance the faulted phase voltage, the negative sequence current from the weak source became unsteady and unreliable for use in decisions by the AVO 1L210 line protection scheme. However, the zero sequence source at the AVO bus behind the relay was strong due to presence of upstream wye-grounded delta transformers. Therefore zero sequence current remained steady and unaffected by the STATCOM control during the fault.

<u>Lessons Learned:</u>
Based on the discussion presented in this section and the results shown in Figure 12, it can be concluded that the zero sequence, instead of negative sequence, current provides reliable ground protection in presence of sources with full-scale power converters contributing to the short circuit currents. The reported event also demonstrated that these sources supply positive sequence current thereby increasing the overall fault current magnitude. But phase overcurrent protection settings will hard to determine using steady-state short circuit analysis because of unknown contribution from power converter connected sources. Therefore phase overcurrent protection must be carefully applied in presence of these power converter sources.

6. Example 3 – Battery and Inverter Source

Photovoltaic or battery storage systems are DC sources that connect to grid through an inverter interface. Most inverters are programmed to balance their terminal voltage and to suppress their negative sequence current output. Thus, their apparent negative sequence source impedance is typically significantly higher than their positive sequence source impedance. On fault inception, they respond to voltage drop and increase positive sequence current to a pre-specified threshold i.e. at their thermal rating. At this level, the inverter almost acts as a current source until the voltage recovers.

In July 2013, BC Hydro installed a 1 MW, 6.5 MWh battery storage and inverter system to enhance supply reliability during sustained power outages to a small remote community. Using data recorded for a double line-to-ground fault, this section illustrates that the negative sequence protection can’t be applied when the relay operating current is solely supplied by the inverter source.

<u>System Description:</u>
Figure 13 shows the distribution feeder one-line diagram and its connection to the storage comprising of 1 MW battery banks which operate between 485 V and 780 V DC. The battery bank connects to 480 V AC system through a 1.25 MVA inverter which then interconnects to the distribution feeder via a 480V/25 kV step-up delta-wye transformer. The wye winding is grounded on the 25 kV side to maintain effective grounding when the Interrupter is open and the community load is supplied by the stand alone storage system.

The inverter has built-in control functions operating on inverter output current. The control limits the inverter output to about 3008 A or 2.0 pu of the inverter continuous rating. Upstream of the inverter, an inverse-time overcurrent digital relay (Device 51 in Figure 13) provides coordinated protection with the entrance fuses of customers connected on the distribution feeder.

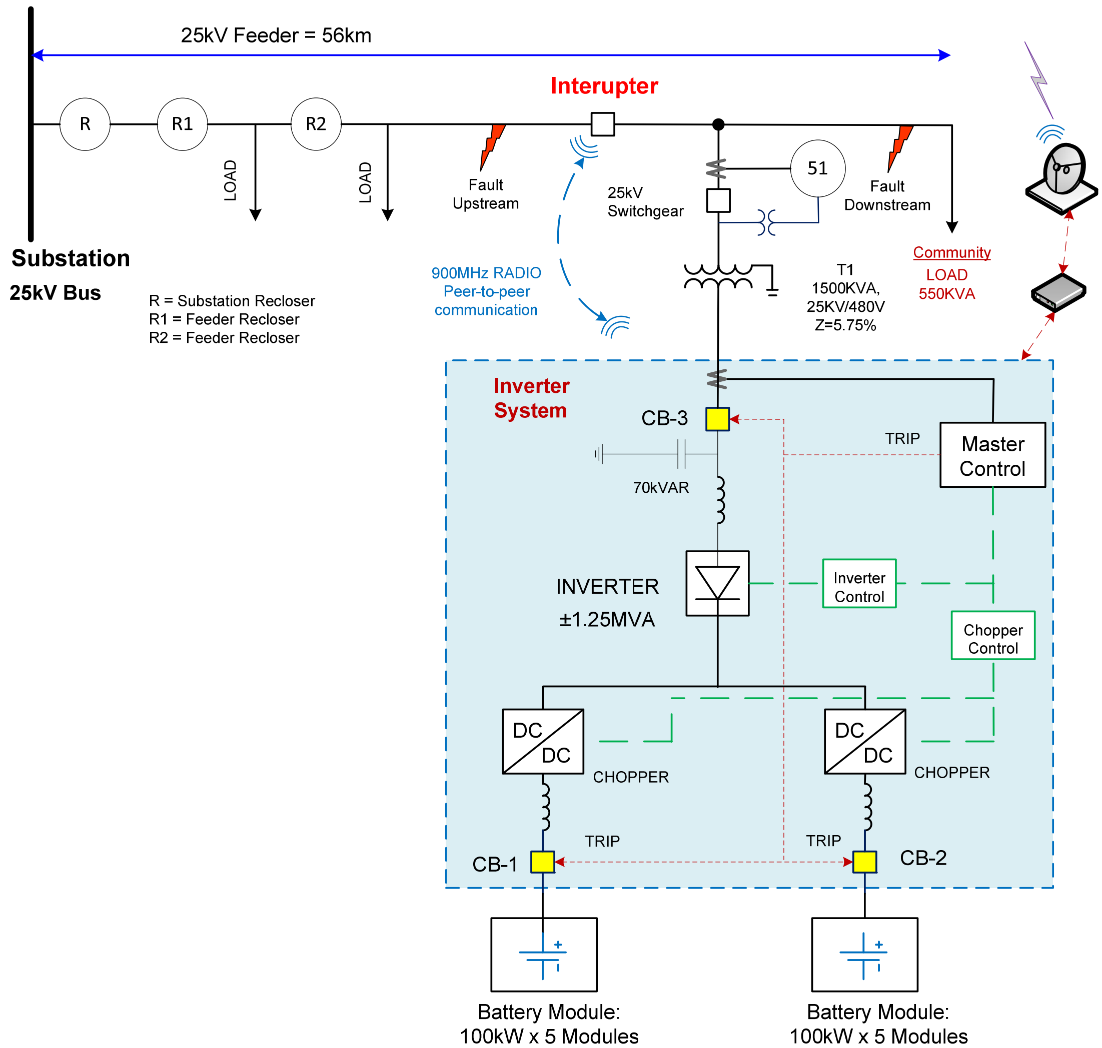


Figure 13: The 25 kV feeder electrical one-line diagram

<u>Negative Sequence Fault Current Characteristic</u>

On 27 July, 2017, the distribution feeder experienced a permanent Phase A-to-C-to-ground fault downstream of the Interrupter i.e on the overhead feeder section between location of battery system and the community load. Feeder protection and inverter protection systems correctly de-energized the feeder. After the Interrupter was opened, the system operator then attempted to restore the community load through the battery system. Because it was a permanent fault, the feeder re-tripped. Figure 14 shows waveforms captured by the inverse-time overcurrent relay (Device 51) when the feeder was picked up onto the close-in 25 kV A-to-C-ground fault. In the figure, the top part has 25 kV three-phase-to-ground voltages. Because it was a solid double line-to-ground fault close-in to the relay location, the voltages on the two faulted phases had completely collapsed and the healthy phase had a severe voltage depression. Traces in upper middle part of the figure are three-phase currents on the 25 kV feeder section, supplied by the inverter through the delta-star transformer. Both two faulted phases had about 100 A rms current which was limited by inverter control to 3008 A at 480 V $\sqrt{3}\times3008\times480/25000$ A = 100A). Traces in the lower middle are magnitudes of three sequence currents. Absence of negative sequence current shows that the inverter source in this application had significantly high negative sequence impedance. The Inverter source was connected through a delta-

wye-grounded transformer which acted as a strong source supplying high magnitude of zero sequence current. The bottom part of Figure 14 has phasor diagrams. Zero sequence current leads the corresponding voltage by about 95° correctly indicating a forward fault direction.

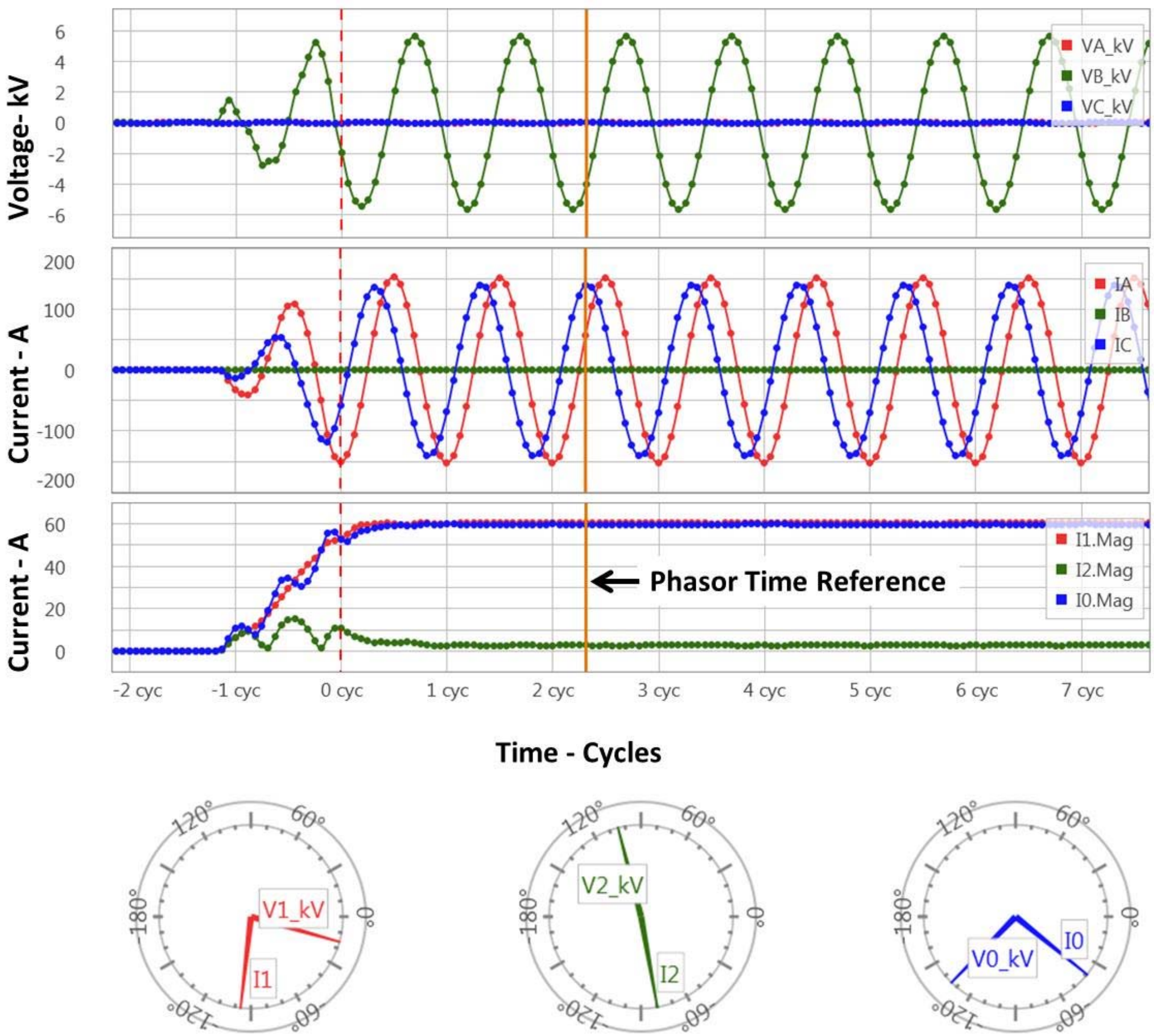


Figure 14: Inverter system system response to line-to-line-to-ground fault.

Lessons Learned:
Short circuit current analysis of the recorded ground fault confirmed that the negative sequence impedance source impedance of the inverter source can be significantly high. Thus, negative sequence current can be too small to use in reliable relaying decisions. Inverter systems are typically ungrounded but they universally connect through a step-up transformer that provides effective grounding to the high voltage network. As seen in examples 1 and 3, the reliability of zero sequence relaying is largely remains unhindered by high penetration of inverter sources as long as these sources are connected using a transformer which provides a path for zero sequence current.

7. BC Hydro Practice

BC Hydro allows interconnection of generators with converter or inverter interfaces to the transmission grid only through transformers that provide effective grounding on the utility side and delta on the generator side. These transformer configurations allow achieving reliable protection for single- or double-line-to-ground faults using the zero sequence current. This section discusses BC Hydro current strategy to achieve reliable protection for all faults, not just the ground faults, on the transmission lines originating from generating stations with interfaced sources. To achieve this goal, either line current differential or Permissive Over-reaching Transfer Trip (POTT) scheme [14] with echo logic is used. This section discusses that both of the schemes require some special design considerations, accounting for uncertainty in fault current from the interfaced sources, to ensure reliable fault detection.

Line Current Differential Protection:
Digital teleprotection channels now allow exchange analog measurements over a long distance between line terminals by numerical line current differential relays. In spite of uncertainty of short circuit contributions, the differential relays can provide reliable phase and ground fault protection for lines interconnecting interfaced sources to the utility grid. As long as the teleprotection channels are secure and available, the line protection will trip both line terminals simultaneously for all in zone faults and restrain for external faults. At each terminal, local stepped phase distance and inverse-time overcurrent directionalized by zero sequence voltage polarized protections are included as backup for the contingency of teleprotection failure or breaker failure during the faults on the adjacent lines connected at the remote terminals. To compensate for the lack of reliable backup phase distance relay operation at the line terminal with interfaced source, supplemental protections are provided. These are time-delayed phase-to-phase under voltage protection and an independent direct transfer trip signal from the line terminal on the utility bus to the terminal connecting the interfaced source.

The line current differential as discussed provides fast, sensitive and reliable protection. The number of tapped loads that can be connected to the line is limited by the design of the differential relay i.e. ability of relay to accept remote inputs via teleprotection channel. Even when the relay system has capacity to accommodate tapped connections, there is higher cost to connect tapped loads due to added cost of digital teleprotection channels for remote measurements.

Permissive Over Reaching –Transfer Trip Scheme:
The high cost of teleprotection channels can restrict application of line current differential scheme when broadband digital telecommunication infrastructure is not available around the new generating station. It may also not be possible to apply the differential scheme if the interconnecting line has several tapped loads. As an example, 2L309 line shown in Figure 5, had multiple tapped loads prior to the interconnection of Quality Wind Farm. As a result, the line current differential scheme could not be applied on this line. In these situations, BC Hydro uses a POTT scheme with echo logic to interconnect the interfaced source stations. The scheme requires less costly communication channel because of limited teleprotection bandwidth requirements and can accommodate tapped loads with relative ease. To achieve reliable and high-speed ground protection, forward/reverse looking zero sequence voltage polarized directional elements torque controlling properly coordinated overreaching instantaneous zero sequence fault detectors are used. For faults not involving grounds, phase-to-phase or three-phase faults where zero sequence current is not present, forward/reverse looking overreaching mho phase distance relays are used. Echo logic compensates for the distance relay not picking up on fault current from the interfaced source when such current is low. Similar to the line current differential scheme, back up and supplemental protections are provided for the contingency of teleprotection failure, breaker failure and phase distance relay failure to operate.

In the POTT scheme, the echo logic also helps with high resistance ground fault coverage but it is not as good as the line current differential scheme. The echo logic is invoked when either the ground protection does not pick up during high resistance faults or the distance relay does not pick up during phase faults at one terminal i.e. the terminal connected to the interfaced source station. As a result, it slows down the fault clearing time by typically about three cycles which includes teleprotection channel (about one cycle) plus echo-back timer (about two cycles) delays.

Supplemental Undervoltage Protection:
As discussed above, the phase-to-phase under voltage protection is provided as backup to the phase distance relays not picking up at interfaced source terminal coincident with the contingency of teleprotection failure. This protection is designed to override the slowest clearing faults on the adjacent circuits. In addition, Figure 15 shows permitted trip zone to ensure that the under voltage protection does not violate low voltage ride through requirements by BC Hydro [15] and North American Electric Reliability Corporation (NERC) PRC-024-01 [16].

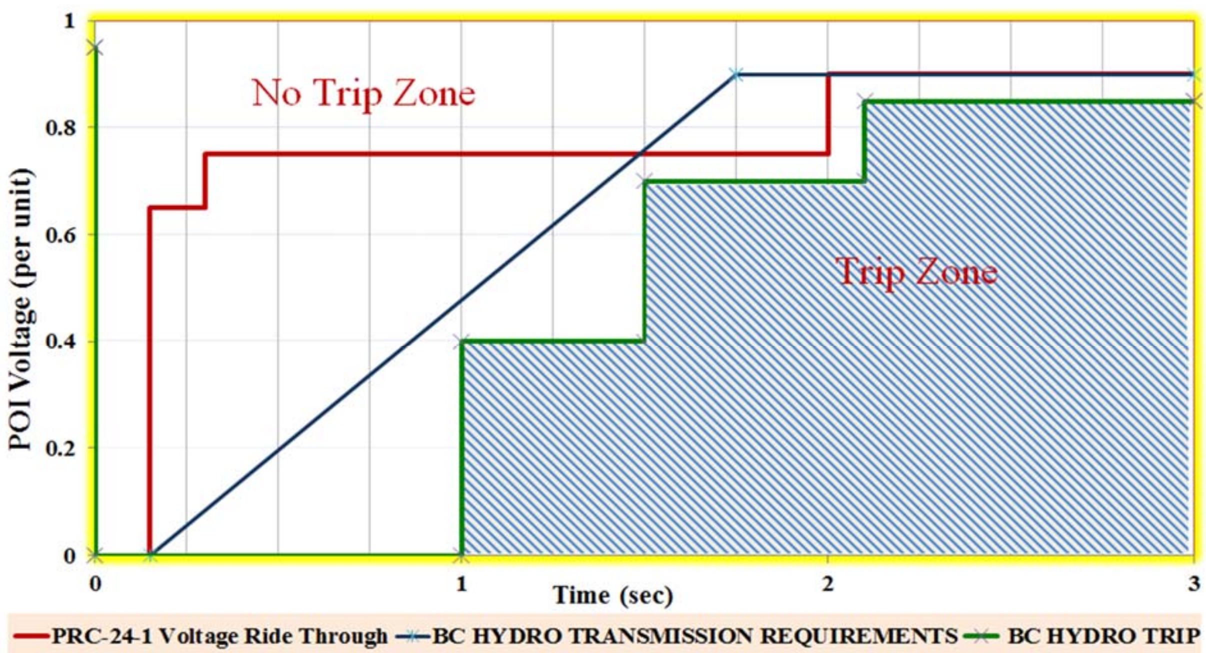


Figure 15: Phase-to-phase under voltage protection trip zone.

8. Conclusions

The majority of utility grid codes do not require connected generators to supply negative sequence currents during system voltage unbalances. Three examples presented in this paper clearly demonstrate that the negative sequence relaying is not dependable to protect the lines connecting interfaced sources i.e. may not trip for in zone ground faults. Further, negative sequence relaying may over trip the line to disconnect the source on external ground faults and thereby obliterate the objectives of low voltage ride requirements. All three examples demonstrated that reliable and effective ground protection scheme, independent of the type of generator and its control configuration, can be designed using zero sequence current as long as the interfaces sources are integrated through transformers which provide effective grounding and serve as source of zero sequence current. Many other faults in BC Hydro system revealed similar weakness in performance of negative sequence ground fault relaying on lines with interfaced sources.

Line current differential and the POTT with echo logic schemes are used in BC Hydro to achieve reliable protection on lines interconnecting interfaced sources. Both schemes are supplemented with time-delayed phase-to-phase under voltage protection at the generating station terminal and a direct transfer trip signal from the utility line terminal to the generating station terminal to compensate for the possible failure of phase distance protection operation. The line current differential scheme is preferred because it provides fast clearing, best ground fault resistance but it limits tap connections of loads to the line. POTT schemes are deployed to avoid high cost associated with the broadband communication medium or when the line has tapped loads. The POTT scheme does not provide as good ground fault resistance coverage compared to the line current differential and provides slow fault clearing when echo logic is invoked.

9. References

1. I. Erlich and U. Bachmann, "Grid code requirements concerning connection and operation of wind turbines in Germany", IEEE Power Engineering Society General Meeting, June 2005.
2. "Fault Current Contributions from Wind Plants", Joint Working Group Report to the Transmission & Distribution Committee, the Electric Machinery Committee, and the Power System Relaying Committee of the IEEE Power and Energy Society 2013.
3. Johan Morren and Sjoerd W. H. de Haan, "Short-Circuit Current of Wind Turbines with Doubly Fed Induction Generator", IEEE Transactions on Energy Conversion", Vol. 22, No. 1, March 2007, pp. 175-180.
4. Sriram Chandrasekar and Ramakrishna Gokaraju, "Dynamic Phasor Modeling of Type 3 DFIG Wind Generators (Including SSCI Phenomenon) for Short-Circuit Calculations", IEEE Transactions on Power Delivery, Vol. 30, No. 2, April 2015, pp. 887-897.
5. R.J. Nelson and H. Ma, "Short Circuit Contributions of Full-Converter Wind Turbines", IEEE PES Transmission and Distribution Conference and Exposition (T&D), May 2012, Orlando, FL, USA.
6. R,A. Walling, E. Gursoy and B. English, "Current Contributions from Type 3 and Type 4 Wind Turbine Generators During Faults", IEEE PES General Meeting, July 2011.
7. Tobias Neumann, Thomas Wijnhoven, Geert Denconinck and Istvan Erlich, "Enhanced Dynamic Voltage Control of Type 4 Wind Turbines During Unbalanced Grid Faults", IEEE Transactions on Energy Conversion", Vol. 30, No. 4, December 2015, pp. 1650-1659.
8. I. Erlich, T. Neumann, F. Shewarega, P. Schegner and J. Meyer, "Wind Turbine Negative Sequence Current Control and its Effect on Power System Protection", IEEE PES General Meeting, July 2013.
9. Ali Hooshyar, Maher A. Azzouz and Ehab F. El-Saadany, "Distance Protection of Lines Connected to Induction Generator-Based Windfarms During Balance Faults", IEEE Transactions Sustain. Energy, Vol. 5, No. 4, pp. 1193-1203, October 2014.
10. Qin-hao Li, Yong-jun Zhang, Wei-peng Yuan and Feng Li, "A Study on Influence of Wind Power on Positive Sequence Voltage Polarized Impedance Relay", Power Engineering and Automation Conference (PEAM0, 18-22 September, 2012, Wuhan, China.
11. "Grid code High and Extra High Voltage", E.ON Netz BmbH, Bayreuth, 1 August 2006.
12. VDE-AR-N 4120, "Technical Requirements for the Connection and Operation of Customer Installations to the High Voltage Network (TCC High Voltage), Jan. 2015.
13. Joe Mooney and Jackie Peer, "Application Guidelines for Ground Fault Protection", 24th Annual Western Protective Relay Conference, October 1997, Spokane, WA, USA.

14. *IEEE Standard C37.113^{TM}-1990 – Reaffirmed 2004, IEEE Guide for Protective Relay Applications to Transmission Lines,* IEEE Power & Energy Society, New York, NY, USA.
15. *60 kV to 500 kV – Technical Interconnection Requirements for Power Generators,* Revision: 1.4, June 2014. BC Hydro.
16. *NERC Reliability Standard PRC-024-1, Generator Frequency and Voltage Relay Settings.*