Disturbance Analysis Enhances the Art and Science of Protective Relaying

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Abstract: Over the last two decades, disturbance analysis afforded by numerical relays has significantly contributed to enhancement of the art and science of protection practices within BC Hydro. Improved understanding of power system behaviour, especially under adverse operating conditions, gained from the analyses has led to refined models or design practices contributing to reliability of protection system. This paper presents a technique to validate parts of the fault study model, as well as a collection of the noteworthy disturbances, associated power system element responses and their impact on the BC Hydro protection system.

1. Introduction

This paper presents examples of what can be learned from analysis of event records generated by protective relays during disturbances. Modern digital relays will normally record sampled data captured before and during disturbances. These data are often equal or close to the quality of data captured by digital fault recorders. Since protective relays are much more widely deployed than fault recorders, the data they capture provides a much more comprehensive picture of power system response to disturbances. The authors hope that this paper will encourage relay engineers to use data captured by protective relays to learn about the response of the power system to disturbances after correct as well as incorrect protection operations.

A technique for validating parts of the conventional fundamental frequency model will be presented to demonstrate cases where better knowledge of the model resulted in better relay settings.

In addition, this paper will discuss the following selected disturbances experienced within the BC Hydro system over the last decade or so. These disturbances were chosen because they enhance understanding of the power system or its elements during abnormal conditions, thereby enhancing protection reliability:

- South Vancouver Island Blackout – one of the contributing factors to this disturbance was a heavily loaded untransposed transmission line, which led to an incorrect decision by the negative sequence directional element. This disturbance provided an improved understanding of the negative sequence voltage created at the receiving terminal for high through current in an untransposed line
- False trips of transmission lines with tapped load transformers – zero sequence contribution from internal tapped load transformers was the cause of misoperation. This key learning from this disturbance improved understanding of the various 230 kV distribution transformer configurations applied in the BC Hydro system with each differing in the zero sequence fault current contribution and its impact on the transmission line protection security.
- Misoperation of a line protection which was supplying large motor loads – the reduction in the source impedance caused by the motors led to mis-operation of negative sequence directional elements. This disturbance led to recognition of the significance of large motor loads in utility short circuit models)
- Trip of healthy unit transformers prior to synchronization – zero sequence over-voltage ground fault detector and/or over-fluxing protection caused the trip during ferroresonance between the VT supplying the relay and the surge capacitor. This disturbance demonstrated that the grounded VTs, connected to an ungrounded system, can ferroresonate even when they are fluxed to the line-to-line voltage rating

The following sections briefly describe each of the above listed disturbances and the cause of the protection relaying mis-operations. Detailed discussion of the lessons learned from the primary system response ensues. Changes to the model representations or relay practices are outlined. The examples presented reinforce other publications that have

demonstrated that disturbance analysis is a valuable tool that enhances the art and science of protective relaying.

2. Background

BC Hydro's transmission system is unusual because overhead shield wires are not used, and transmission towers often have high footing resistances. Some 230 kV lines are more than 100 km long and are not transposed. The absence of overhead shield wires provides significant savings in transmission line construction (approximately 15%), but makes the power system vulnerable to lightning faults. High tower footing resistances due to granite geology requires sensitively set ground fault relaying. For example, the 230 kV line protection schemes are designed to detect ground faults of at least 100 ohms, which is among the highest in North America. Thus, designing of line protection schemes requires a precise balance between the ability of the protection system to detect a fault, and to remain secure during abnormal system conditions. Traditionally, BC Hydro applied permissive overreach transformer trip (POTT) schemes with echo logic having a sensitively set zero sequence fault detector and zero sequence polarized directional elements.

Over the last two decades the transmission system has become more and more constrained with increased loading on the system. During the same time period, BC Hydro started staged replacement of aging electromechanical relays with new microprocessor-based relays. The availability of new relaying features in the modern devices has led to shifts in protection philosophies to improve the reliability of the increasingly constrained transmission system while maintaining the ground fault detection sensitivities. One of the major shifts was in the POTT scheme where the zero sequence polarized directional element was substituted with the negative sequence-voltage polarized directional element. This helped improve line protection security on parallel lines with mutual coupling. Also, the sensitively set zero sequence ground fault detector was replaced with a negative sequence detector to maintain the ground fault protection sensitivity under heavy loading. Lines with tapped load transformers or some dead-looped lines (with no source of negative sequence current) continued to use zero sequence fault detectors. Adaptation of the new relaying technology with new features added to flexibility and led to improvements in the systems over the years. Some of these were realized from the disturbance analysis feature, which provided better understanding of the power system behaviours under abnormal conditions when security of the relay systems, operating close to the limits of sensitivity, were challenged.

3. Fault Study Model Validations

Relay event reports are well recognized as a useful means of checking transmission line impedances calculated by a line constants program, when the location of a fault is known [1]. However, the fault location is not always known, since most faults are temporary. Further, not only transmission line impedances, but also transformer and generator impedances make up an important part of the power system model.

If a relay is measuring all the current passing through the source impedance, the measured currents and voltages during a fault can be used to calculate the source impedance and validate a fault study model. The calculated source impedance will be independent of the fault location and fault resistance. Reference [2] shows the details of the technique, but the principles are presented here for convenience. An example of an evolving fault on a distribution bus as shown in Figure 1 will be used.
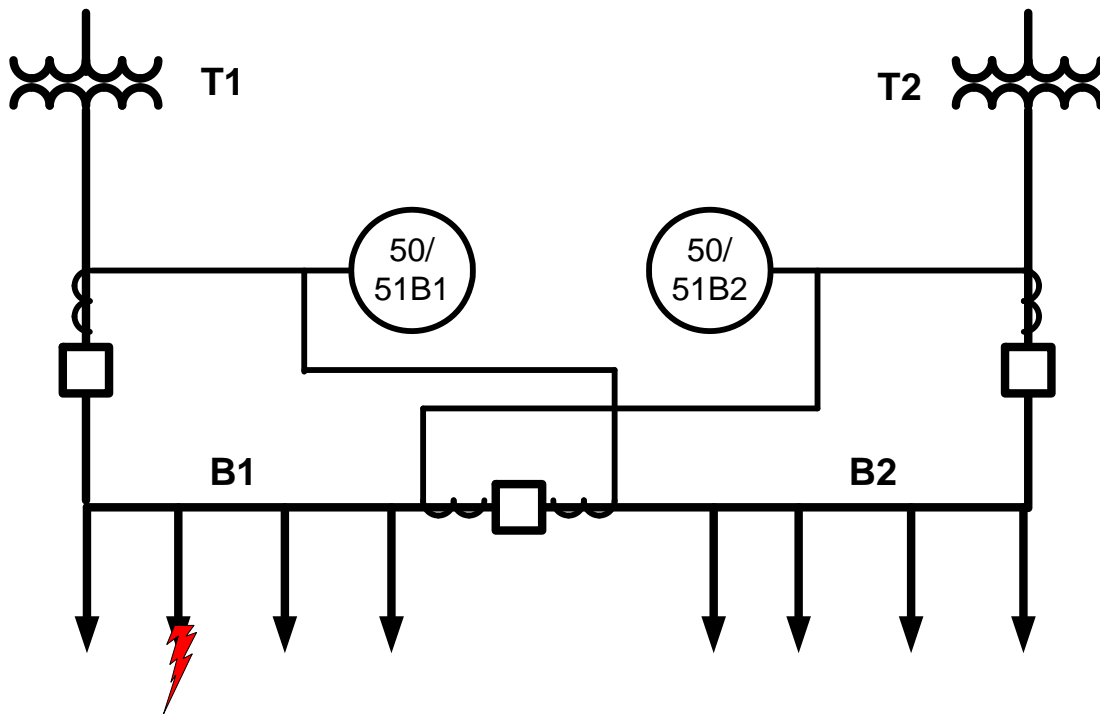

Figure 1 - Close-in fault at a distribution station

The fault record from Device 50/51B1 will be used. Figure 2 shows the plot of the fundamental frequency phasors with respect to time. The currents measured are the currents to one of two distribution busses that are supplied at a certain station. The plot is labeled as "oscillographic like" because a true oscillographic plot would plot instantaneous values which include all frequencies up to the cut-off of the anti-aliasing filter. Figure 2 is actually a plot of time varying fundamental frequency phasors. The magnitudes of the negative and zero sequence currents are also plotted in the same figure. The evolution of the fault from B-G to B-C-G results in a change in the values of the negative and zero sequence currents.

Since the fault study model is a steady state, fundamental frequency model, the data from the relay event reports are filtered to show only the fundamental frequency component. The filtering process will take a finite period of time, so the model validation is only possible when the filter has stabilized to a steady state value.
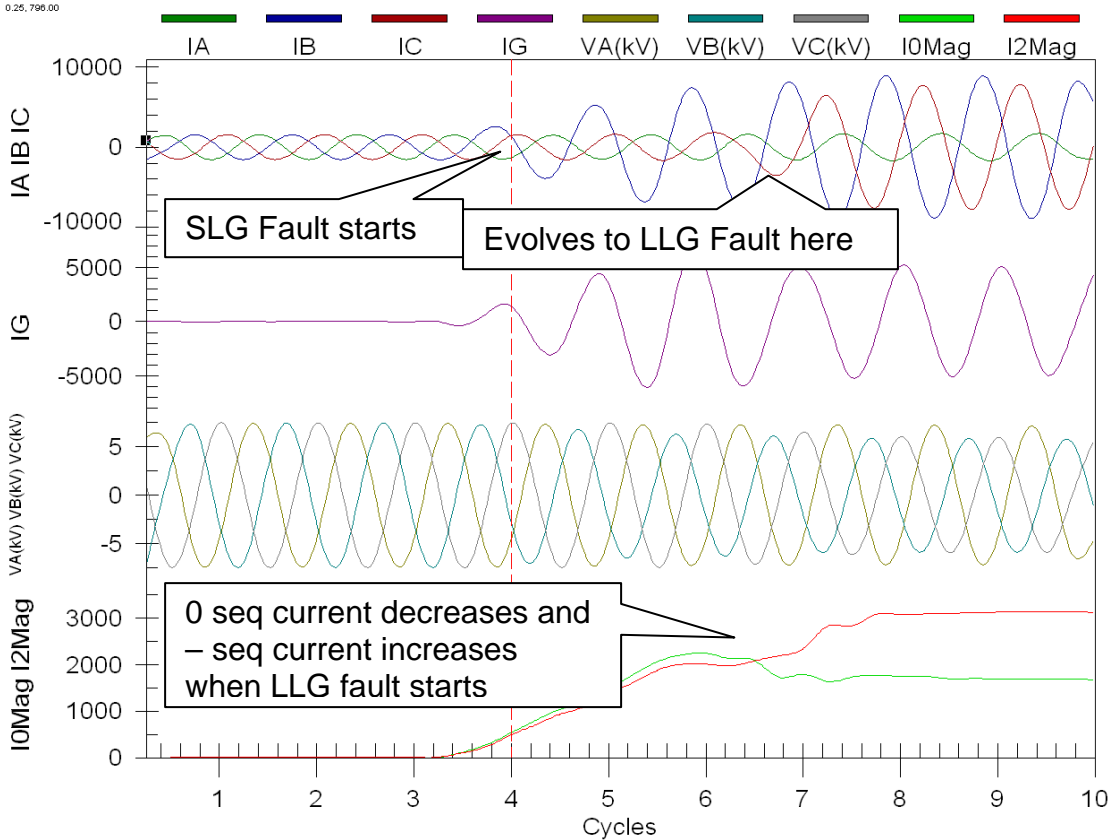
Figure 2 - Filtered "oscillographic like" fundamental frequency values
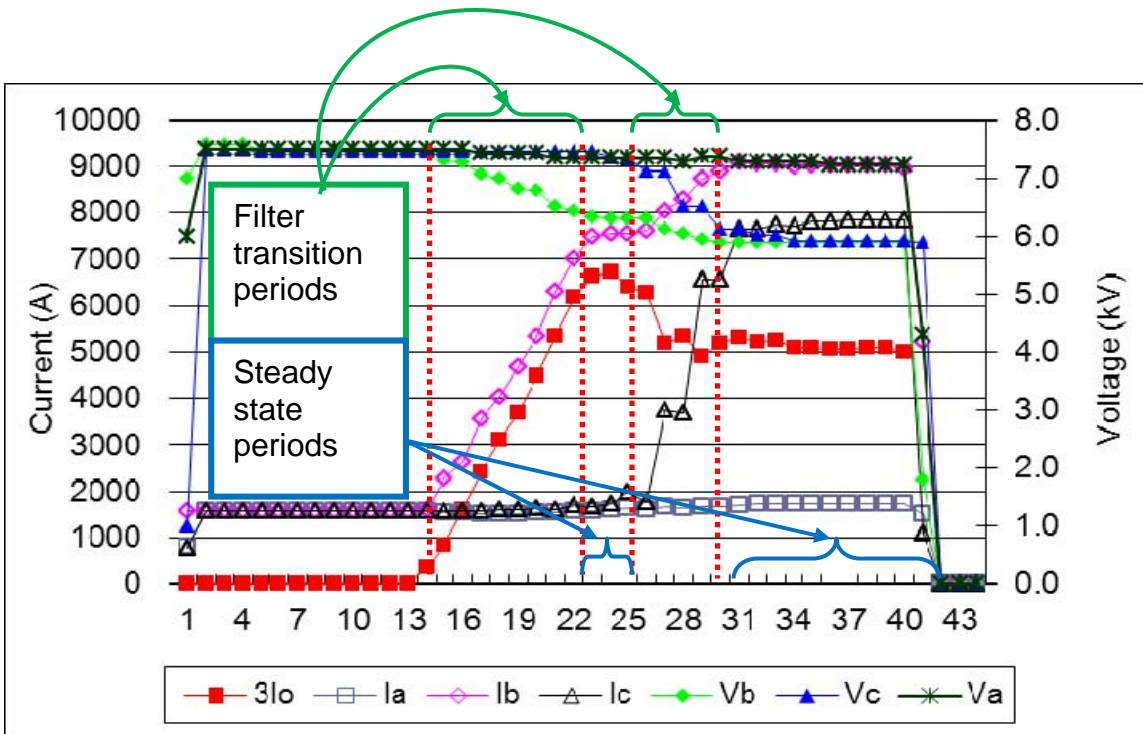

Figure 3 - Plotting magnitudes reveals steady state periods

Figure 3 shows plots of the magnitudes (plotted at quarter cycle interval) of all phase current and voltage phasors and the residual current during the fault record. The transitions from one steady state to the other can be readily appreciated with this type of plot. It is only during steady state conditions that the fault study model may be validated. Symmetrical positive, negative, and zero sequence quantities can readily be calculated from the recorded three phase quantities. Plots of their magnitudes (as in the lower two traces of Figure 2) will also show when filter stabilization occurs.

Symmetrical components are often used for unbalanced fault analysis. The source impedances that form part of the sequence networks which are used in symmetrical component analysis are shown in Figure 4. Note that the direction of current is assumed to be positive when flowing out of the network towards the fault location.

Figure 4 - Thevenin Equivalent Source Impedances in Symmetrical Components

Given the directions of currents and voltages shown in Figure 4, the calculation of the negative and zero sequence source impedances is simple:

$$Zs2 = -Vr2 \,/\, Ir2 \qquad (1)$$

$$Zs0 = -Vr0 \,/\, Ir0 \qquad (2)$$

Calculation of the positive sequence source impedance is a little more difficult, because the equivalent voltage Es behind the source impedance needs to be known. This is sometimes difficult to estimate accurately from a relay event record, because of the effect of pre-fault load currents. If these are large, and not all measured by the relay, it may not be possible to calculate Es from the event record.

However, if the entire pre-fault load current is measured by the relay, the effect of the unknown Es can be eliminated as follows. Under pre-fault conditions,

$$Es = Ir1' * Zs1 + Vr1' \qquad (3)$$

where the prime (') mark indicates pre-fault currents and voltages. Under fault conditions,

$$Es = Ir1 * Zs1 + Vr1 . \qquad (4)$$

Es can be eliminated from the two equations (fault and pre-fault) to yield the positive sequence source impedance from the measured currents and voltages:

$$Zs1 = (Vr1 - Vr1') / (Ir1' - Ir1) \qquad (5)$$

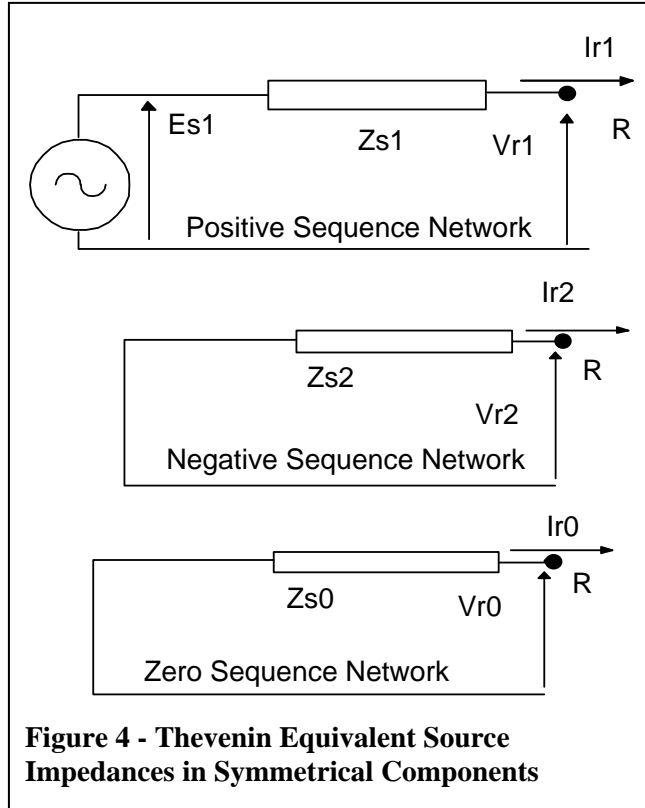From the above equations, it can be seen that the negative and zero sequence impedances behind the relay can be calculated from the measured fault quantities, as long as all the fault current through the source impedance also flows through the relay. The positive sequence source impedance behind the relay can also be calculated from the fault and pre-fault quantities, as long as all the load and fault current that flows through the source impedance also flows through the relay.

The requirement that the relay measure all the current that flows through the source impedance limits the applicability of the measurement to simple radial systems, or two machine systems. If there are connections behind the relay to the remote terminal of the protected equipment, through which significant fault current flows, the source impedance cannot normally be calculated from a single relay event record.

The positive, negative, and zero sequence source impedances behind the relaying point can be calculated by the process described above and plot as shown in Figure 6, Figure 5, and Figure 7. In these figures note that the positive sequence source impedance is not measured as accurately as the negative sequence, because the source impedance to the fault location also serves some load from Bus B2 in Figure 1 which is not measured by
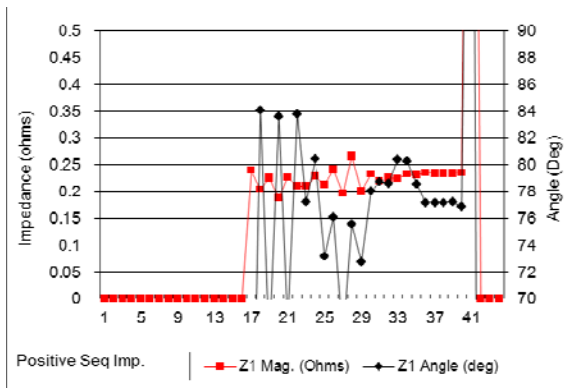

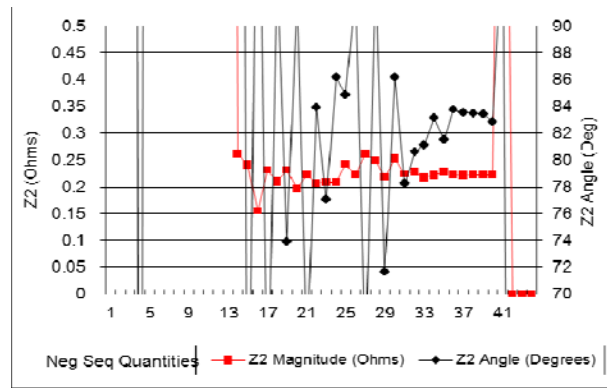**Figure 6 - Positive sequence source imp.**

Figure 5 – Negative Sequence source imp.

Device 50/51B1. Therefore, Device 50/51B1 does not accurately eliminate the unknown value Es in Equations (3) and (4) above. However, the negative and zero sequence impedances are accurately measured, and were able to be compared to the source impedances to the distribution bus as computed by the fault study. Errors were found to be negligible, in the order a few percent. In other cases, errors in the fault study have been noted, as is pointed out later in this paper.
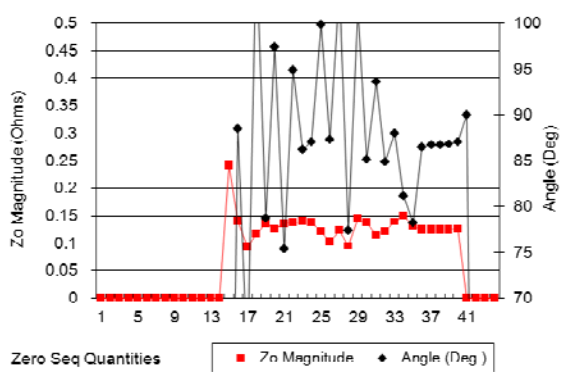

Figure 7 - Zero sequence source imp.

4. Impact of Untransposed Line Unbalance

The BC Hydro system has some long untransposed 230 kV lines. Lack of transposition introduces internal unbalances, which were not taken into account while setting sensitive ground protections for the 230 kV and lower voltage lines until the misoperation of the protection of a 100 km long untransposed line under heavy load. As discussed in this section, the disturbance provided useful insight into the internal negative and zero sequence voltages generated in an untransposed line when it is supplying a balanced load or fault.

The Incident

On 12th October 2008, a fallen tree branch caused a phase to phase short circuit on a 60 kV circuit. This fault triggered a series of cascading transmission line trips that eventually led to a blackout of the South Vancouver Island (SVI) region. The region was without power for several hours until the transmission and distribution system could be restored.

A condensed one line of the South Vancouver Island system is shown in Figure 8. The initially faulted 60 kV circuit was 60L87.
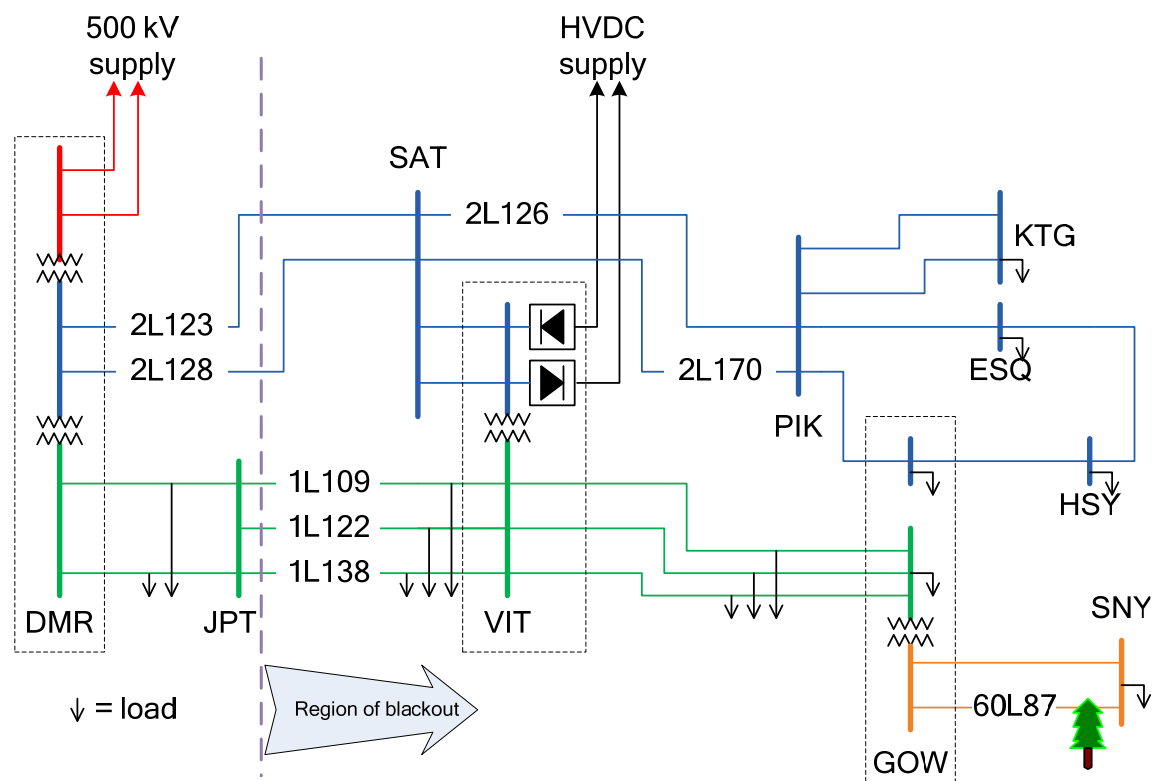

Figure 8 - Condensed One-line diagram of South Vancouver Island

The main cause for the escalation of this disturbance into a wide area outage was the unexpected misoperation of protection systems on the two transmission lines (2L123 and 2L128) that form the backbone 230 kV supply to the SVI area. These two POTT protection systems misoperated sequentially for different reasons. The loss of 2L128 by one problem triggered the subsequent loss of 2L123 by a different problem.

The 60L87 fault was cleared correctly. An unexpected trip of 2L128 was the first misoperation. This was caused by a setting error which resulted in incomplete coordination between the forward looking elements at DMR with the reverse looking elements at SAT. While unacceptable, this misoperation was easily analyzed and the incorrect settings corrected.

When 2L128 tripped off line, 2L123 became more heavily loaded than it had ever been before (though still within rated capacity). Even though the protection on 2L123 was correctly set in accordance with BC Hydro existing guidelines at the time, the unbalance in circuit 2L123 (caused by lack of transpositions combined with heavy load) resulted in negative sequence voltages and currents that were sufficient to cause the sensitive forward looking directional elements at **both** terminals of the line to declare a forward fault and trip through the POTT scheme.

After both 230 kV lines tripped, the 138 kV circuits between JPT and VIT tripped on the ensuing power swing. The result was the complete loss of supply to South Vancouver Island.

Analysis

Unless transmission lines are fully transposed, positive sequence load or fault current flowing through the line will result in zero and negative sequence voltages being induced along the line. The mathematical process for deriving the coupling coefficients are given in the paper "Introduction to Symmetrical Components", by Zocholl and Schweitzer [3]. Due to the non-zero off-diagonal elements in the sequence impedance matrix, imperfectly transposed (or untransposed) lines will have negative and zero sequence voltages induced along them due to positive sequence current flowing through them. These voltages will then drive negative and zero sequence current flows through the line. The important thing to note is that because the voltage source is **inside** the line, directional elements at both ends of the line will tend to see these quantities as a forward fault. Note in the example (Figure 9) below, that relays at both ends of the line see V2 lagging I2 for internal unbalances.
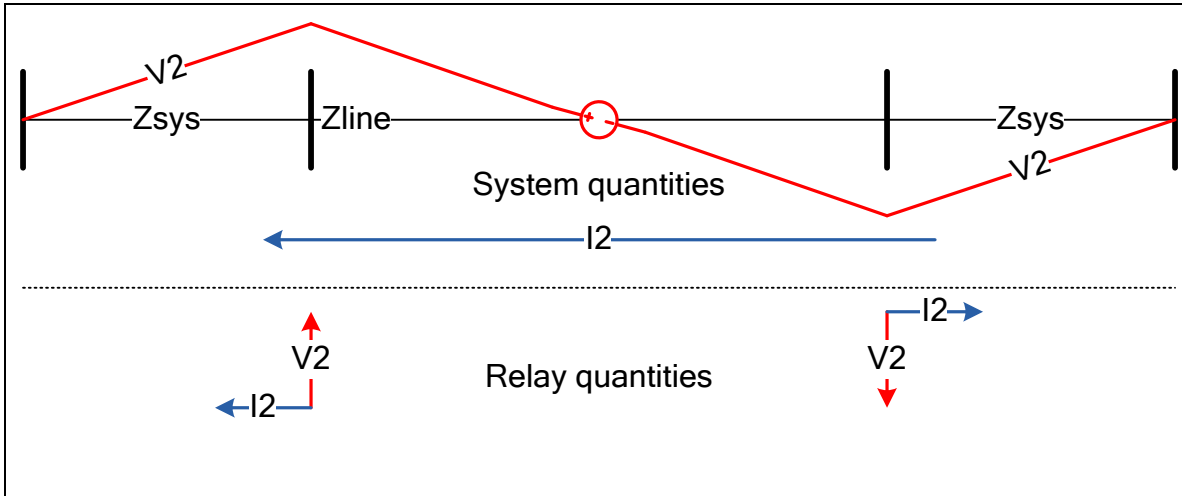
Figure 9 - Negative sequence directional elements operate for internal unbalance

Since the voltages and currents induced in the line via these inter-sequence coupling impedances cannot be differentiated from actual fault currents, the protection must either be desensitized to accommodate the maximum through load current or other means must be found to regain the security of the line protection. Many line protection relays allow positive sequence restraint of directional elements, whereby the ratio of I_2 to I_1 must exceed a certain ratio before the negative sequence directional element will be allowed to operate (similarly for zero sequence directional elements). BC Hydro had earlier set this restraint setting to a rather low value to ensure that the protection systems retained their sensitivity under high load conditions. This misoperation showed that this practice threatens security.

Determining the appropriate value for the positive sequence restraint setting started off as a non-trivial exercise. The actual ratio of I_2 to I_1 in a given line depends not only on the physical line geometry, but also on the positive and negative sequence source and load impedances in the system. However, in the worst case, very low system impedances can be assumed, with this being a reasonable assumption in a meshed system. By neglecting system impedances, the ratio of I2/I1 approaches Z_{21}/Z_1 (where Z_{21} is the line's positive to negative sequence coupling impedance, and Z_1 is the positive sequence impedance of the line). The value of Z_{21} depends on the amount of asymmetry in the inter-conductor distances (delta configurations are good, flat configurations are bad), as well as the ratio of the conductor GMR to the GMD (bundled conductors typically fare worse than single conductors). Calculated ratios of Z_{21}/Z_1 in the BC Hydro system ranged from approximately 0.12 (for a flat configuration, 2 conductor bundle) down to very nearly zero for a delta configuration.

5. Impact of Tapped Transformers

As discussed in Section 2.0, new line protection POTT schemes in BC Hydro use negative sequence polarized directional element and zero sequence over-current fault detectors on lines that have tapped distribution or customer load transformers. Since

most distribution or customer transformers have delta winding connecting the transmission system, the zero sequence fault detector provides immunity from misoperation from faults on the distribution or low voltage system. However, BC Hydro's station planners applied different winding configurations to the 230 kV system as discussed later in this section. This section reports a disturbance which was valued for providing the key learning how these different winding configurations or the core construction impact sensitive ground fault security.

Figure 10 shows the 230 kV sub-network interconnecting Ingledow (ING), Arnott (ARN) and Strawberry Hill (SYH) substations. ING is a strong transmission substation supplying ARN, which has a very weak active source behind it. The ARN source is so weak, that ARN forms a dead-loop for positive and negative sequence currents for faults on the 230 kV lines between the two substations, which are about 17 km apart. The 230 kV auto-transformers with delta tertiary winding at ARN are strong sources of zero sequence current.

SYH is a distribution substation and is tapped from three of the four 230 kV lines approximately 2.5 km from the ING substation. Two 230/25 kV transformers (T2 and T3) were installed in 1990. These transformers are wye-grounded at 230 kV and delta with a zigzag grounding transformer at 25 kV. T1 is a relatively new transformer (installed in 2003) and it is wye-grounded at 230 kV but with only zigzag grounded winding at 25 kV.
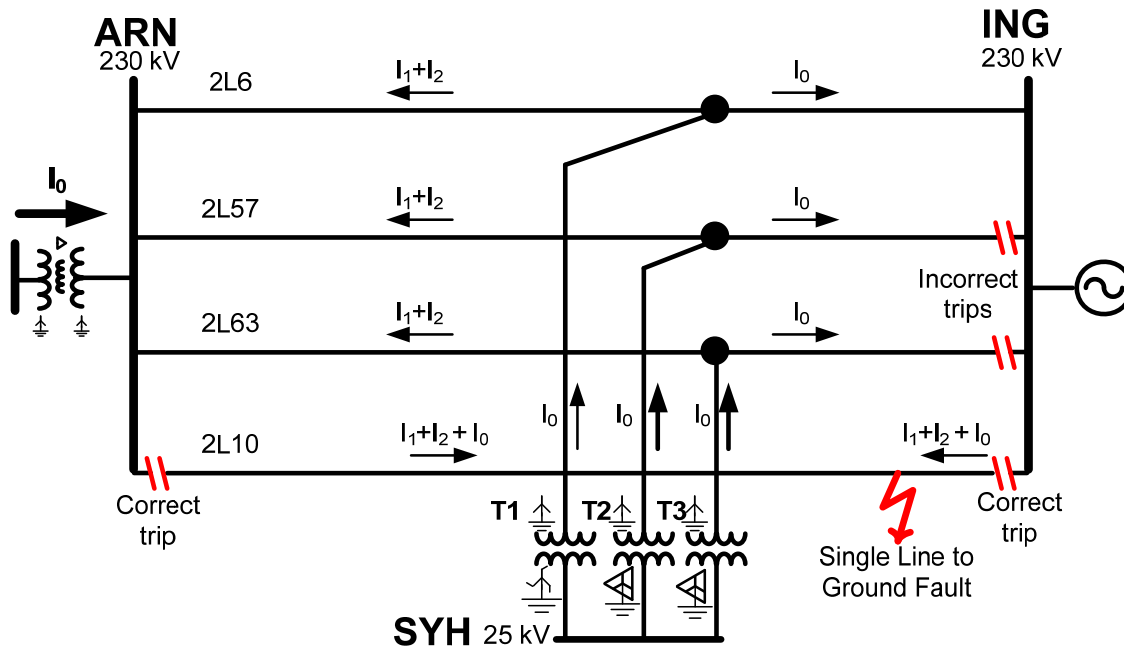

Figure 10 - ING ARN SYH Sub network showing distribution of sequence currents

All line protections are POTT schemes with echo logic and negative sequence directional elements. However, unlike most BC Hydro lines where the POTT schemes also use negative sequence over-current fault detectors for the ground protection, the tapped SHY transformers prevented the use of negative sequence ground fault detectors on 2L6, 2L57 and 2L63. These lines use zero sequence over-current fault detectors for protection security to the unbalanced faults at 25 kV bus on Strawberry Hill. The 2L10 protection scheme uses negative sequence directional elements and fault detectors.

The Incident

On 16 March, 2005, 2L57 and 2L63 false tripped at ING coincident with a single line to ground fault on 2L10 whose relay records identified a B-to-ground fault about 5 km (or 25%) from ING. Figure 11 is a record from the 2L10 relay at ARN terminal showing fault initiation and clearing. About 4-cycles into the fault, the increased current indicated fault clearing at the remote terminal (ING) followed by the ARN terminal clearing fault in about 7 cycles. The slow opening at ARN indicated potential breaker problems because the nominal interrupting time is 3 cycles. Though the 2L10 protection cleared the fault, the analysis helped in identifying a potential breaker failure problem.
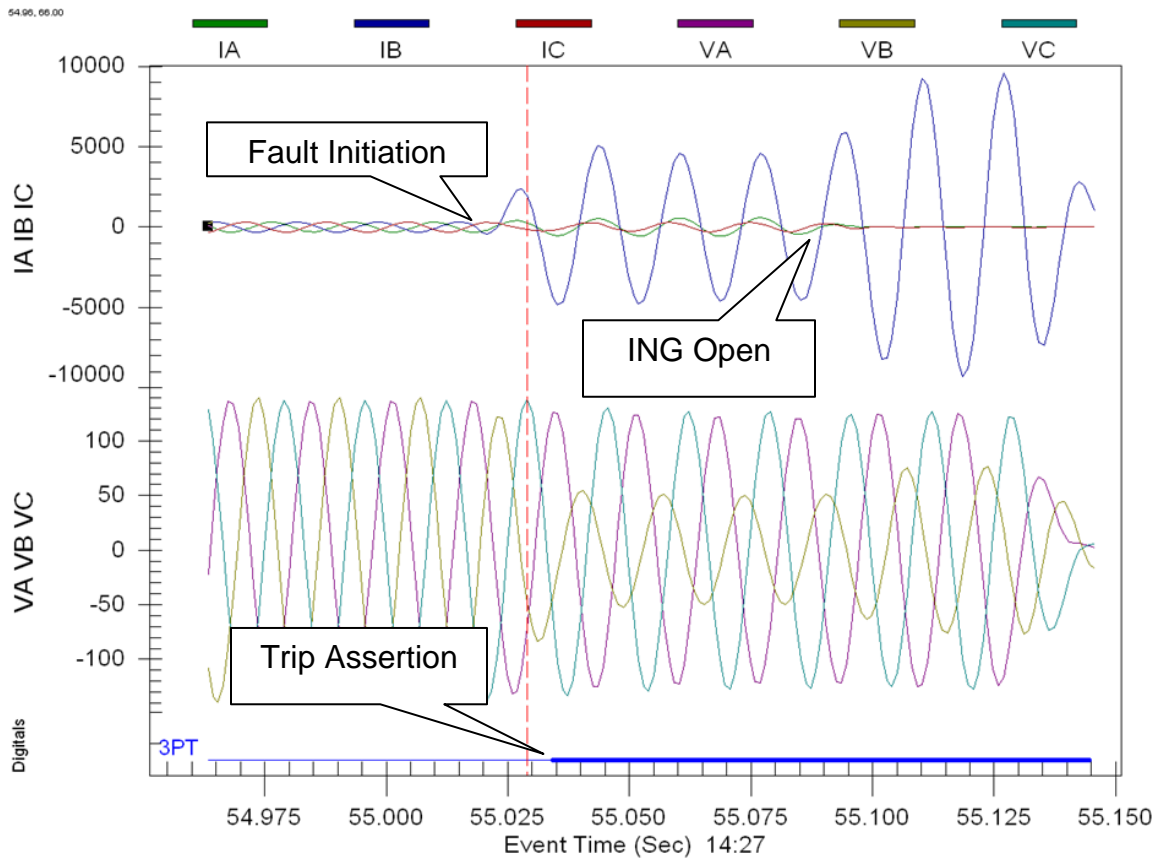

Figure 11 - 2L10 relay records from the Arnott terminal

Analysis

Since 2L57 and 2L63 did not trip at ARN, only records from ING were available. Using the available relay record and short circuit simulations, the cause of misoperation was inferred. Figure 12 shows 2L57 fault data recorded by the relay at ING. The records from 2L63 were similar. At the initiation of the record, the zero sequence fault detector (50N2) and negative sequence forward directional element (32QF) were asserted indicating the forward ground fault (67N2) signal including initiation of the permissive keying to the remote terminal (ARN). Receipt of the permission trip a few cycles later indicated its echo return from ARN causing trip at the ING terminal. Recognizing the value of having fault records for both terminals, even when only one line terminal trips, BC Hydro has now modified its practice to trigger the fault records whenever the relay keys permissive trip via the echo logic.

In the short circuit simulator, all three SYH transformers were modeled almost identically. Though T1 has a different configuration, it was represented almost identical to T2 and T3. All three transformers are sources of zero sequence current albeit T1 being weaker than T2/T3 as discussed in the next section. Figure 10 depicts distribution of positive, negative and zero current in the 230 kV sub-network from simulator. The proximity of the fault to ING and the SYH transformers (sources of zero sequence current) caused enough current to flow from the 2L57 and 2L63 to the fault via ING to cause 50N2 to assert. Most of the positive and negative sequence fault currents contribution from ING was directly into 2L10 but some portion fed through the healthy lines forming a dead-loop via ARN because has only a weak active source behind it. With the current distribution as shown in Figure 10 for the healthy lines, the negative sequence directional elements saw a forward fault at ING and a reverse fault at ARN. With the ING fault detector picked-up and forward fault indication by directional element, two out of the three healthy line protections sent permissive trip to ARN. 2L6 did not have fault detector asserted as discussed in the next section and thus did not initiate permissive trip. Zero sequence in-feed from SHY transformers and the inherent high zero sequence path impedance prevented the flow of zero sequence current into the healthy lines from ARN. Thus the zero sequence fault detector at ARN did not assert to prevent the echoing of permissive trip back to ING. Both the reverse directional element and the fault detector have to be asserted to block permissive keying and echoing.
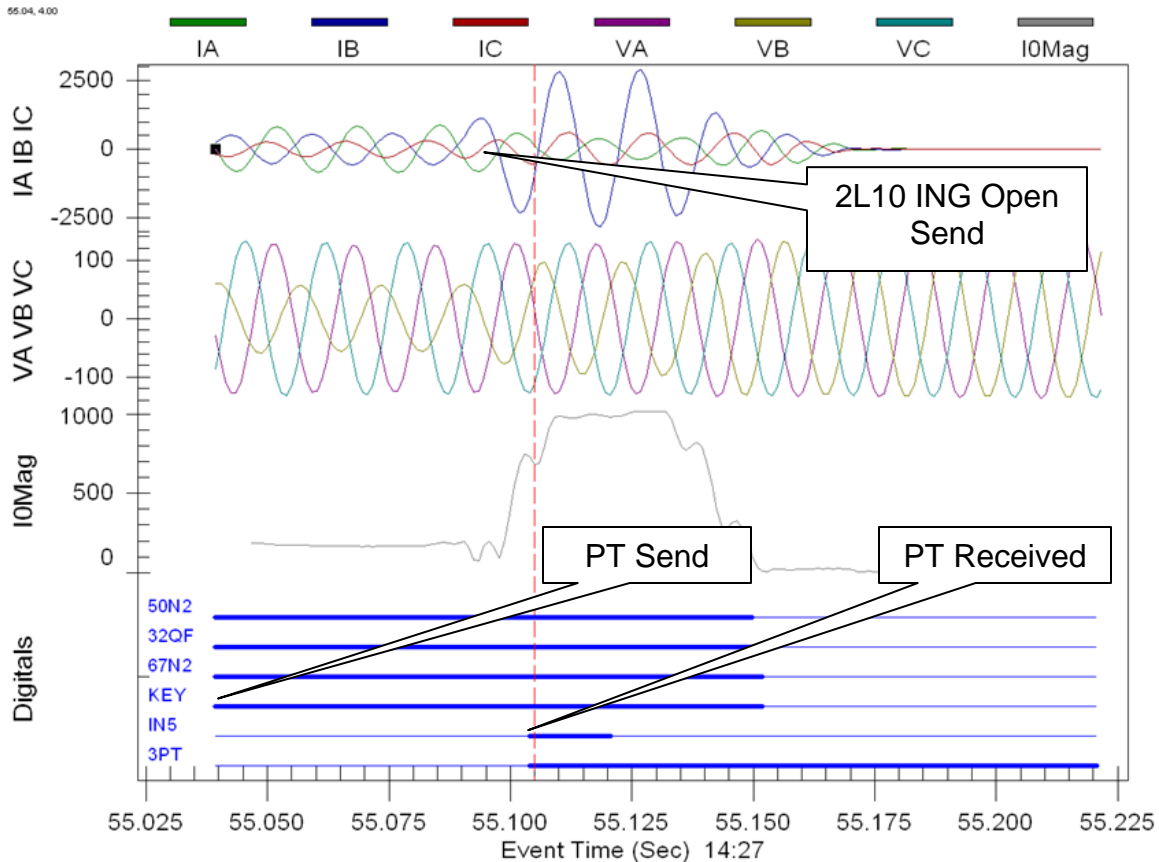
Figure 12 - 2L57 relay records from the Ingledow terminal.

Mitigation

Transmission lines between the two terminal substations, ING and ARN, run on the same right-of-way. Thus application of the negative sequence directional element, as part of protection upgrade, avoided the problem of incorrect directionality decisions for external faults on adjacent lines which are zero sequence mutually coupled. In this case, T2 and T3 have grounding transformers, which are strong sources of zero sequence currents as explained in the next section. The proximity of the fault to ING prevented their contribution via ARN. Insufficient flow of zero sequence line current at that terminal eventually led to misoperation.

To avoid similar mis-operations, reverse looking negative sequence fault detector were added at the both terminals. These reverse fault detectors had the same sensitivity as the local reverse directional element i.e. more sensitive than the forward directional element at the remote terminal. Addition of the properly coordinated negative sequence fault/directional elements would block echo of the remote permissive trip and thereby enhance the security of the scheme.

It was recommended to apply three-terminal line current differential protection in future for similar applications when the broad-band link among the stations is available.

230 kV Distribution Transformer Configurations

Distribution or load transformers typically are delta configuration on the high-side and are not a source of zero sequence current. Thus, the BC Hydro POTT schemes on lines with tapped load or distribution transformers using zero sequence fault detectors were generally deemed secure. This incident highlighted weakness of the scheme and is worthy of some discussion. All BC Hydro distribution transformers below 230 kV have delta configuration for the high voltage winding. However, the eventual standardization of the winding configurations of the 230 kV transformers underwent some evolutionary process as described below.

Often ground faults or switching condition in the transmission system results in temporary back-feed through the delta winding when two or more delta/wye distribution transformers are connected at low-voltage bus. For 69 and 138 kV, there is provision in the various equipment standards to accommodate temporary un-grounding. BC Hydro makes use of this temporary capability in arrangements to permit temporary back-feed (for a few seconds) into ungrounded lines via delta connected transformers. There is no such provision for non-effectively grounded system operation at 230 kV and higher. Consequently when BC Hydro started to step-down directly from 230 kV to distribution voltage, the need was recognized for a transformer with HV winding configuration other than a delta connection that was a zero sequence source to maintain the ratio $Xo/X_1<3$, should there be back-feed to the HV via the LV. Another objective for the grounded wye HV winding is to permit graded insulation on the winding and most importantly, permit the HV tap changer to be located at the neutral end of the winding.

An early approach to this was the delta-grounded transformer proposed by a Mr. Hoeppner and subsequently known as the Hoeppner transformers [4,5]. These Hoeppner transformers were specified by BC Hydro for a number of years and a variant[1] exists at a number of stations. In this configuration the transformer behaves as a high voltage grounded wye – low-voltage delta transformer for high-side ground faults. High voltage system unbalance due to a ground fault results in a vector sum voltage in the delta that drives HV zero sequence current toward the fault in the faulted phase winding with corresponding circulating current in the delta that matches the positive and negative sequence current in the unfaulted phase windings providing ampere turn cancellation in those phases. Like any wye-delta transformer the zero sequence impedance is about the same as or slightly lower than, the positive. There were two problems with the Hoeppner connection. One was load sharing between the parallel zigzag and delta windings on the LV winding was not under full design control so both windings were uneconomically over dimensioned. The other problem (applicable to the variant design as well) was that the HV wye LV delta resulted in these units being strong zero sequence sources and thus gave the protection problems for radial circuits and line taps similar to misoperation discussed above.

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[1] A separate zig-zag grounding transformer within the tank is provided.

The solution to the problem came when new transformer design methods permitted the development of a HV grounded wye LV zigzag transformer. As such there is no delta winding to couple the phases during HV unbalance. If this were five legged core the impedance of the HV winding to unbalanced faults would be the magnetizing impedance, effectively infinite for practical purposes. By utilizing a three legged core, there is a path for in-phase zero sequence core flux through air and the surrounding structure such as the tank that gives the effect of a high impedance virtual tertiary and allows modest zero sequence current to flow, driven by the vector sum of the unbalanced flux in the three legs of the core [6] and as shown in Figure 13. The zero sequence impedance of the HV wye winding is high due to substantial flux leakage as determined by the internal clearances to iron parts together with flux shielding methods. The HV zero sequence impedance can be controlled to a limited degree by design. BC Hydro specifies 40-50% (based on ONAN rating) zero sequence impedance on the HV side to achieve effective grounding ($X_0/X_1 < 3$) while still reducing the impact on the transmission ground protection.

With the better understanding of transformer configurations and their impact on zero sequence impedance, the improved security of the 2L6 protection scheme can now be explained. SYH T1 is a newer transformer and has a zero sequence impedance, on the 230 kV side, of 57% on the ONAN rating (1.14 pu on 100 MVA). This impedance is about five times higher than the 10.6% on the ONAN rating (0.24 pu on 100 MVA) of the older T2 and T3 transformers. Thus, zero sequence current infeed from SYH T1 via 2L6 into the external fault was below the fault detector setting at ING and did not precipitate the line protection mis-operation. Relatively high zero sequence impedance of the new 230 kV distribution transformers led to the improved line protection security while providing the desired level of grounding in case of back-feed.

This disturbance contributed to an enhanced understanding of the various 230 kV transformer configurations encountered within the BC Hydro system and their impact on sensitive ground protection systems. It also contributed to a correct model representation of the SYH T1 Transformer in the short circuit model.
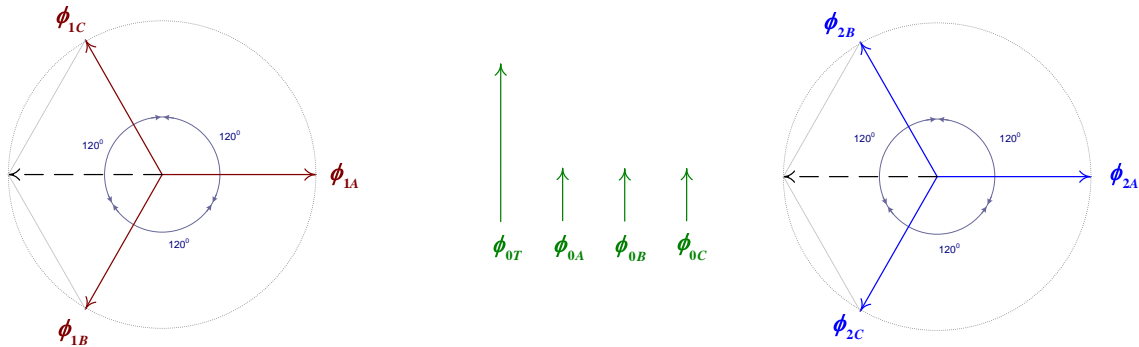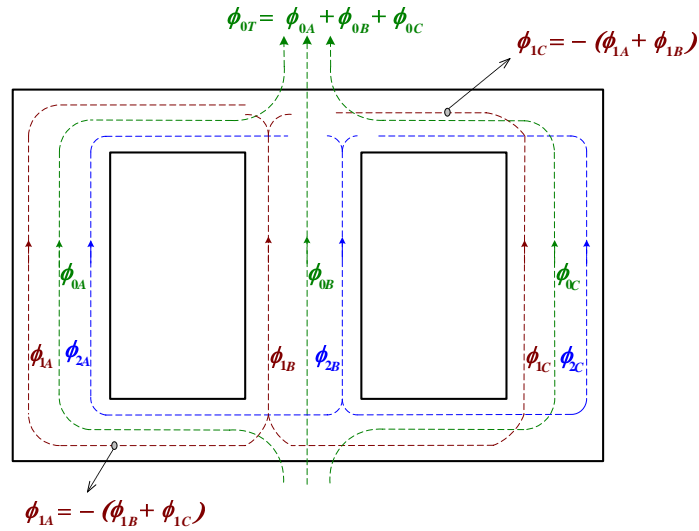
Figure 13 - Flow of unbalance flux in a three core transformer.

6. Large Motor Loads Affect Transmission Line Protection

BC Hydro supplies several large industrial loads at transmission voltages. These large loads are primarily pulp and paper mills with a large component of motor loads. The motor loads are usually neglected in transmission system fault studies. However in some cases these loads can have a significant impact on transmission line protection settings. Disturbance analysis can be used to identify the impact of large motor loads and help determine modeling parameters to represent these motors.
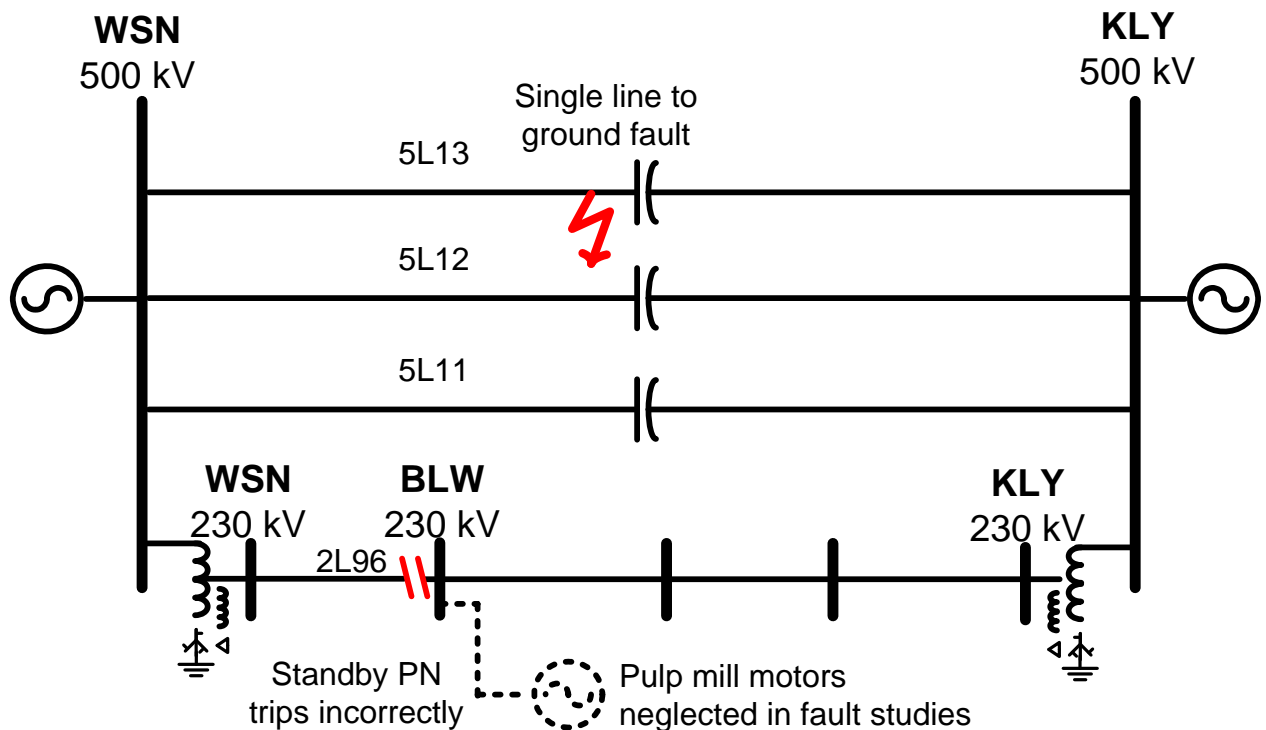
The Incident

Figure 14 - Simplified system diagram

On 7 August 2008, a 230 kV transmission line (2L96) tripped incorrectly after one of three parallel 500 kV lines (5L13) suffered a single line to ground fault and opened its C phase to clear the fault in a single phase tripping and reclosing sequence. Figure 14 shows a simplified representation of the power system with the line of interest (2L96) identified by terminals WSN and BLW. 2L96 is protected using modern transmission line protection relays using fault detectors and negative sequence directional elements.

Relay fault records showed that, after the fault on 5L13 and while its C phase was open, 2L96 primary and standby protections at BLW terminal saw a forward fault and sent permissive trip signals to the remote WSN terminal. WSN standby protection did not initiate a reverse blocking function which is normally expected for an external fault seen by protection at the other end of a line. As a result, WSN standby protection echoed the received permissive trip signal and 2L96 BLW terminal was tripped by its standby protection.

Since there was no fault record being initiated and no trip from the identical 2L96 WSN primary protection, the reverse looking element is assumed to have correctly blocked echo of the received permissive trip from BLW.

Analysis reveals insecure directional element settings.

There are two approaches to setting the thresholds of the directional elements which use negative sequence impedance measurements for directional decisions.

- Set on the basis of half the line negative sequence impedance (Z2)
- Add the strongest possible (minimum) negative sequence source impedances at the terminals to the line impedance and then set the elements to half of this total impedance

BC Hydro chooses the latter approach, which offers the advantage of reducing the impact of negative sequence voltage measuring errors while maintaining maximum possible sensitivity. The former approach, recommended by the manufacturer and based only on the transmission line data, has the major advantage of being independent of system changes (i.e., reduction in negative sequence source impedances at the line terminals).

A previous paper [7] describes in detail how the negative sequence directional settings are determined in BC Hydro line protection applications. Using the BC Hydro practice, Figure 15 shows the negative sequence impedance plane for 2L96 as seen from the WSN terminal and the directional element's forward (Z2F) and reverse (Z2R) settings determined. These settings were in-service when the mis-operation occurred.

To identify the reason for the absence of a blocking signal from WSN, the relay fault record of WSN 2L96 standby protection at the instant of receiving the permissive trip signal was analyzed. Figure 15 also shows the fault impedance (measured z2) as seen from the WSN terminal and dynamic forward threshold (Z2FTH) and reverse threshold (Z2RTH) at the instant of mis-operation. The dynamic thresholds were calculated manually from the 60 Hz phasors by the relay records and the Z2F/Z2R settings using the method described in the relay reference manual.

Notice that the fault impedance plot z2 in Figure 15 is just in between the forward (Z2FTH) and reverse (Z2RTH) thresholds. This resulted in the relay declaring neither forward nor reverse fault. Thus the WSN standby protection did not block echo of the received permissive trip and caused the incorrect trip of the Barlow terminal. It seems that the WSN primary protection correctly declared a reverse direction since it did not echo after also receiving the permissive trip signal from BLW.
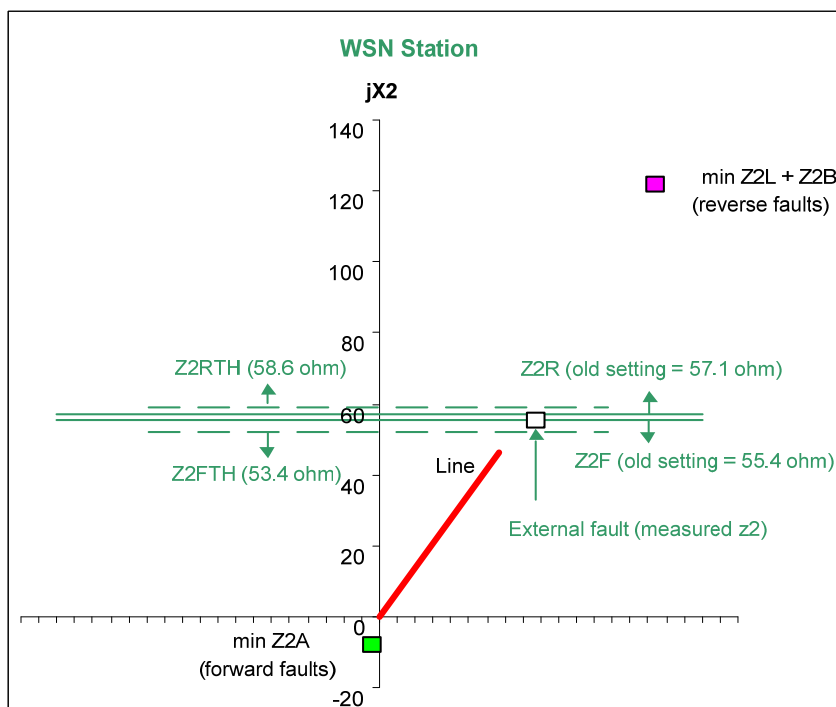
Figure 15 - WSN standby protection sees neither forward nor reverse for external unbalance

Further review of the BC Hydro fault study model revealed that ignoring of some large motor loads connected in the BLW area led to higher values of negative sequence source impedances which were responsible for the insecure Z2F and Z2R settings.

Motor loads of about 150 MW are connected in the BLW area, either through 230 kV lines or 66 kV lines. These motor loads were not simulated in the BC Hydro fault study model which provided the negative sequence source impedances used in determining Z2F and Z2R settings in Figure 15. The influences of these motors are remarkable for some substations. For example, the negative source impedance of BLW station decreases from 76 ohm to 58 ohm after considering these motor loads. To validate the fault study model, the negative sequence source impedance of BLW station was measured using the method described in section 3 and using disturbance data from a previous line to ground fault on 2L96. The measurement showed that BLW has a negative sequence source impedance even lower than the value determined with the motors modeled with the measured value being 51 ohm. The analysis has revealed that with the motor loads modeled, the fault study model better matches real life.

Mitigation

After incorporating motor loads into in the fault study model, the Z2F and Z2R settings for all transmission lines in the area were recalculated.   New Z2F and Z2R settings for WSN 2L96 line are presented in Figure 16. The dynamic forward (Z2FTH) and reverse

(Z2RTH) thresholds were recalculated at the instant of mis-operation with new settings and are also shown. It can be noted that, if these settings were applied, WSN 2L96 protections would have properly identified the fault as reverse, and no false-trip of the line would have occurred.
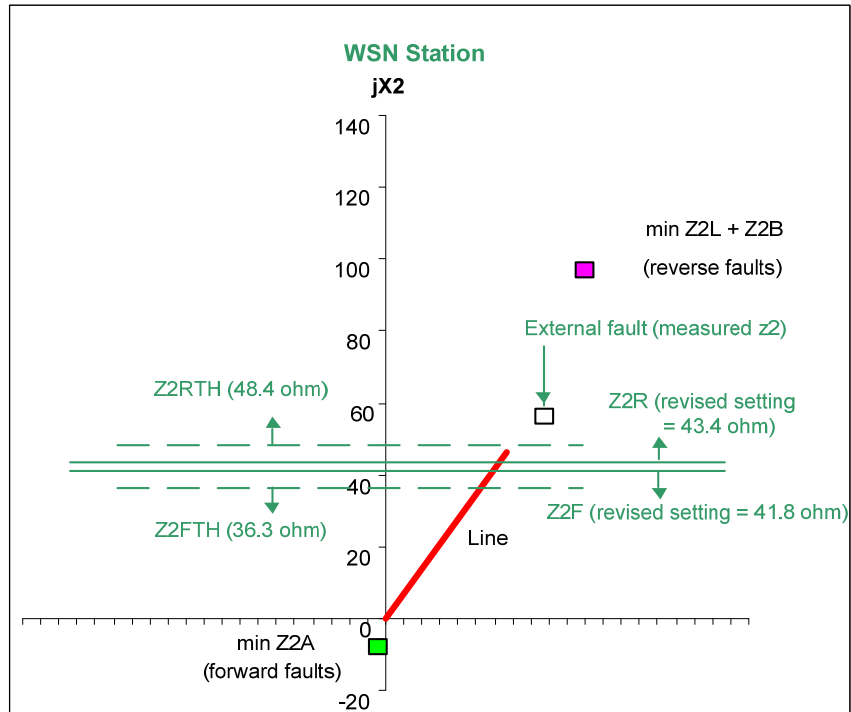

Figure 16 - Revised Z2F and Z2R settings considering lower Z2s behind BLW

Note that some time before the above described incorrect trip of 2L96 happened, a line-to-ground fault had occurred on 2L96. However, since the protection systems correctly responded, there was no significant effort expended on disturbance analysis or to validate source impedances at the line terminals. A lesson learned is, that analysis of correct protection operations can lead to improved system models, which can potentially avoid mis-operations.

7. Trip of Healthy Unit Transformer Prior to Synchronizing

Voltage transformers (VTs) with flux rating suitable for line to line voltage are used when they are connected phase to neutral in an ungrounded system. This flux rating avoids VT saturation during neutral swings and prevents their magnetizing reactance becoming ferro-resonant with the connected (if any) and stray capacitance. In last few years, BC Hydro had a few generator unit transformers trip when they were only connected on the HV side but not to the generator (i.e. with the LV unit circuit breaker open). These trips were caused by the time-delayed over-voltage and/or over-flux (volt per Hertz) element(s) in the modern relays connected to grounded three-phase VTs. They

had occurred only in the plants where the protection systems along with instrument transformers were replaced. During the replacement program, it was decided to connect the relays to three single phase grounded VTs because this arrangement provides better records of the voltage waveforms than the traditional open-corner delta VTs, which traditionally had an over-voltage relay with a loading resistor in parallel connection. Since the new relays are capable of internally deriving zero sequence voltage from the three single phase-to-ground voltages, this arrangement was preferred with the new line-to-line fluxed VTs deemed adequate to avoid VT saturation.

The review of waveforms from the unfiltered relay records of the incidents indicated that the VT were ferroresonating at the time of trip notwithstanding their high flux rating. This section reports one such incident from Strathcona Generating Station in BC Hydro, where high-side breakers of the transformer tripped on several occasions before or during synchronization of the unit circuit breaker. The unfiltered waveforms from the relay records were an excellent aid to understand the ferroresonance phenomenon. The analysis also led to improvements in the design practices to prevent sustained ferroresonant condition.

Figure 17 shows a simplified one-line diagram of Strathcona generating station. This station has two generators (G1 and G2) having their own unit transformers (T1 and T2). The synchronization is performed across the unit breakers. The unit transformer T1 has an 0.1 µf surge suppression capacitor connected on its low-voltage side. On the high-side, the two unit transformers share a common bus with no tripping device providing segregation between them. Thus the protection trips of either unit transformer causes full station outage (sometimes with lockout).
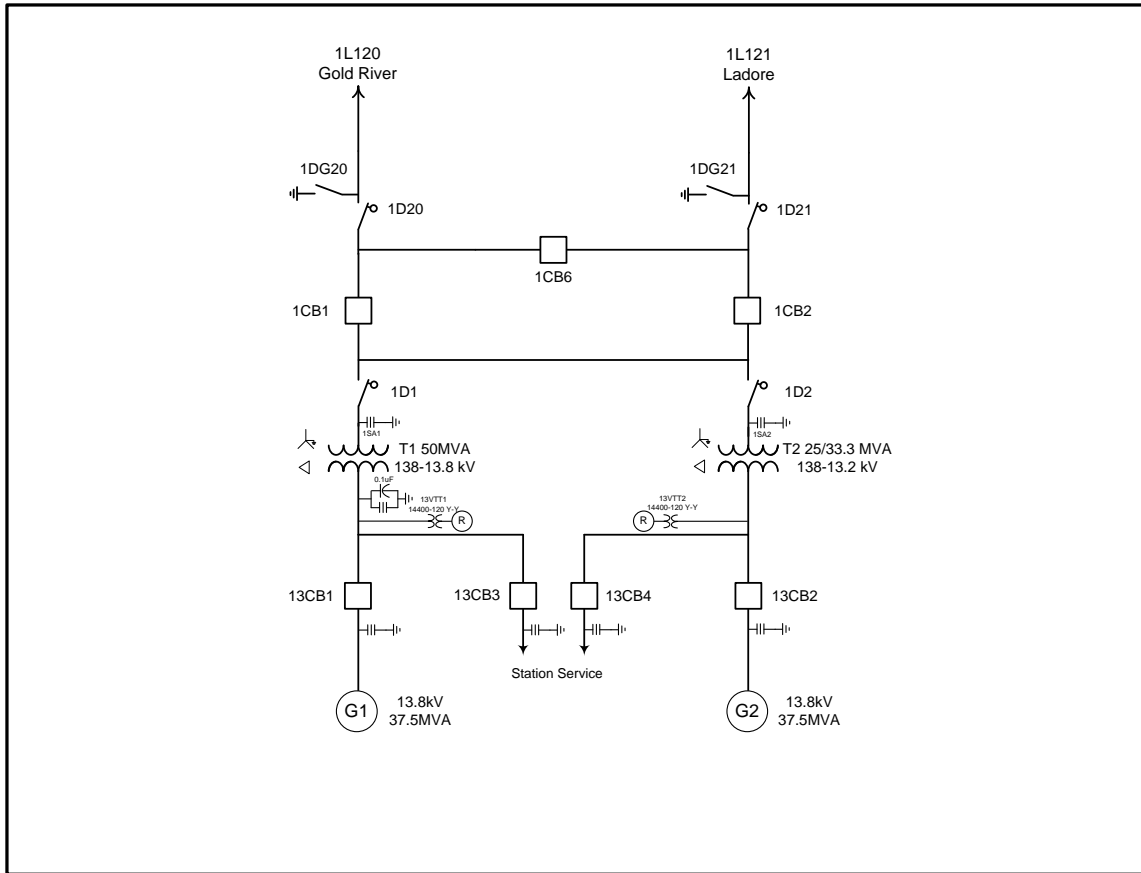
Figure 17 - Simplified One-line Diagram of Strathcona Generating Station

The Incident

On 14th August 2010 at 6:04 AM, the unit transformer T1 at the Strathcona generating station experienced a protection trip. Prior to the trip, the unit and station service breakers (13CB1 and 13CB3) were open. 1CB1 and 1CB2 tripped causing a complete station outage and killing the station service. G1/T1 had a history of recurring trips. Occasionally G2 also had a similar problem but mostly as a result of G1 induced tripping. Nine days earlier, this unit transformer had experienced a similar outage. After that disturbance, it was tested and put into service only the day before this incident. The relay records from 14th August trip confirmed that the trip was caused by definite time-delayed over-fluxing (volts per hertz) element. Since the transformer health was confirmed from tests before energization a day before, a rigorous waveform analysis of the relay records was undertaken. The unfiltered records were thus requested and shown in Figure 18.
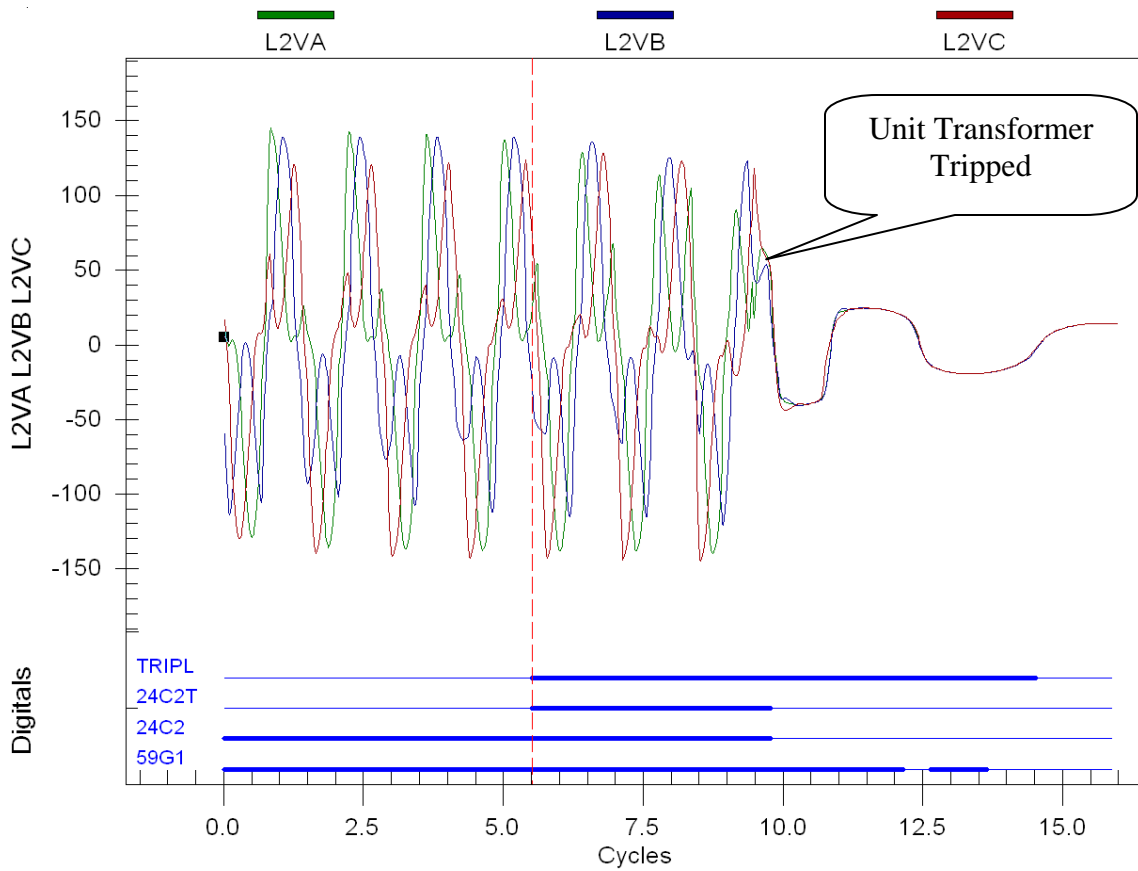
Figure 18 - Relay records from a trip suspected to be initiated by pt ferroresonance

Analysis

This over-fluxing condition was not in the unit transformer (or main power apparatus) rather it was in the three-phase grounded VTs supplying inputs to the relay. It was caused by what appeared to be a ferroresonance condition. This conclusion was based on the following observations from the relay records in Figure 18:

- The highly distorted waveforms with excessive zero sequence voltage as seen by the continuously assertion of the zero sequence over-voltage (59G1) element. The station also registered time-delayed zero sequence over-voltage alarm before the trip was issued by the over-fluxing (24C2T) element
- Following to the unit transformer tripping and disconnection of the 60 Hz source from primary winding of the VT, low-frequency zero sequence oscillations continued as seen in the waveforms from 10-cycle onwards – indicating the resonant condition between the VT (only magnetic element connected) and capacitance (surge suppression and stray capacitance)
- The crest value of the recorded voltage is about 140 V where as it is expected to be 94 V (=1.414 × 66).

The simplified circuit diagram in Figure 19 is provided to illustrate that magnetic pt and the system capacitance in an ungrounded system form a parallel circuit, which can become resonant only in the ground or zero sequence mode. Presence of low-frequency voltage distortions mostly containing zero sequence components was indicative of the ferroresonance condition.
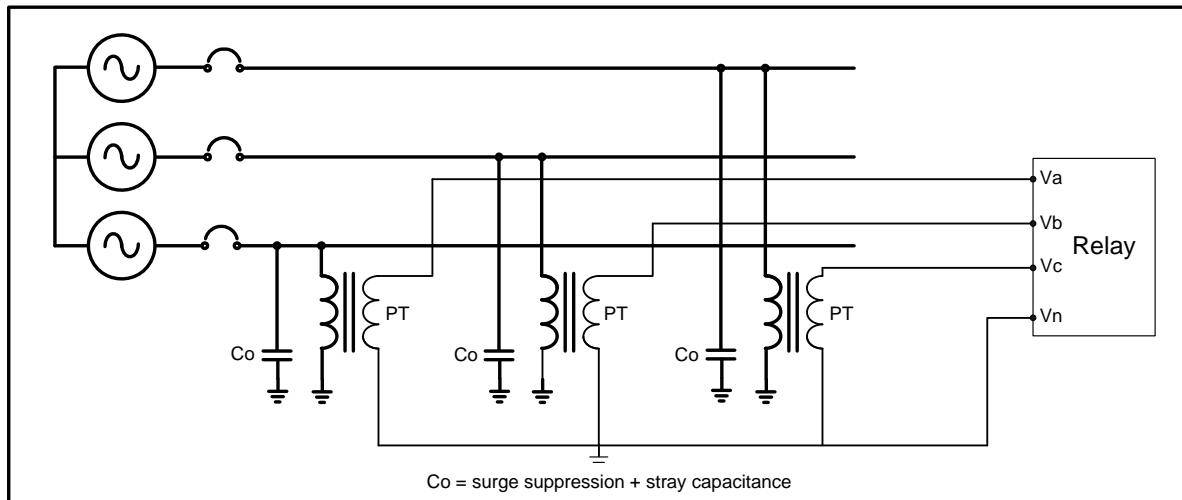

Figure 19 - Circuit Diagram of Magnetic VT and the System Capacitance in Ungrounded System

Though the VTs with flux rating of line-to-line voltage are less prone to saturation and ferroresonance, the T1 operation with the unit breaker open and presence of 0.1 µf capacitor allowed sustained ferroresonance condition to established following to a switching transient condition such as opening of station service breaker. Switching transient could cause one or more of the three single phase VTs to saturate thereby creating conditions to resonant with the parallel shunt surge suppressant capacitor and causing high zero sequence voltages.

Mitigation

The pt was electrically tested and visually checked after this incident. The tests provided satisfactory results. Further, it did not to have any external signs of overheating. The system was permitted return to normal operation except with a condition placed on Generator G1. It had to continuously run with the unit circuit breaker closed as a short-term solution. The long-term solution required either adding an auxiliary pt with secondary connected in open corner configuration with a loading resistor. The new designs apply dual secondary windings – one three-phase grounded pt for connecting the relay and the other in open-corner delta configuration with the loading resistor. Reference [8] provides a method for calculating a suitable loading resistor. Since the resistor is connected across open-corner delta secondary winding, it adds to pt burden or losses only during the conditions when the system develops zero sequence over-voltages.

8. Conclusions

Disturbance analysis has revealed several previously unknown characteristics of the power system that affect protective relaying performance. Since protective relays are expected to discriminate between normal and abnormal conditions it is essential for the protection engineer to understand the characteristics of the power system under all conditions.

Most protection applications and settings are based on a fundamental frequency steady state (fault study) model of the power system. This model has proven to be valid for the majority of application and setting calculations. Analysis of disturbances from correct as well as incorrect relay operations can help to validate or refine the fault study model.

Some important power system phenomena such as transmission system unbalance and ferroresonance are not modeled by the fault study. Disturbance analysis can help in the understanding of these phenomena and in mitigating the problems caused by them.

The data capture facilities of modern protective relays offer a view of the power system during disturbances that was not available historically. Engineers will find value in studying disturbance records after correct as well as incorrect operations to learn more about the power system that the relays protect.

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