CHALLENGES ENCOUNTERED IN THE OPERATION ANALYSIS and SETTINGS OF A PARALLEL THREE-TERMINAL LINE APPLICATION

By: Jeffrey Pond, National Grid; Ashok Gopalakrishnan, Electrocon; Tony Giuliante, ATG Consulting

INTRODUCTION

Protection for three terminal lines can be complex and protection for two parallel three terminal lines are even more complex. There are many conditions to consider [1, 2] when applying protection to a three terminal line such as strong and weak sources, mutual coupling, and sequential tripping if one terminal clears first. Another factor to consider is the use of a newer generation relay from a different manufacturer when converting a two terminal line into a three terminal line.

National Grid experienced an over trip of a Directional Comparison Blocking (DCB) Scheme on a 115 kV double-circuit mutually coupled line for a transformer lightning arrestor failure on a parallel three-terminal line with an identical DCB scheme. The post-fault investigation identified the root cause of the event as improper application of relay settings. As a result of this operation a coordination check and relay settings review was performed resulting in the relay settings being recalculated and the adjusted settings applied at all three terminals. After the settings were applied the relays were tested using traditional relay testing methods. End-to-end relay testing to verify the protection schemes operation by applying simulated internal and external faults was considered, however, an outage to perform the tests could not be arranged. Therefore, once the settings were applied and the relays tested, the directional comparison blocking protection schemes were placed back in-service.

Several questions arose as a result of this over trip event. First, how can a misapplication of relay settings be avoided in the future? Second, if end-to-end relay testing of the scheme cannot be scheduled, what other methods can the protection engineer use to attain confidence that the relay settings have been properly applied? Third, what applications are available to help the protection engineer ensure that the relay settings are properly applied?

This paper will attempt to answer these questions by reviewing the over trip of the parallel DCB scheme for the lightning arrestor failure, and a review of the setting philosophy for three-terminal DCB relay schemes. Then a comparison of the initial relay settings and the new settings will be done based on the relay setting philosophy. The paper will conclude by discussing the results obtained using a short circuit simulation tool to perform a coordination check using both the initial and newly applied settings. The intent is to determine if the improper application of relay settings could have been detected using the simulation techniques. This will assure the protection engineer that the settings will work properly for protection of the transmission line.

SYSTEM EVENT ANALYSIS

The System Control Center reported that on January 11, 2008 at 10:53:25 a lightning arrestor on transformer 1 at the West Cranston substation, which is connected to the S171S line, failed due to a lightning strike (Figure 1). The S171S Line tripped clearing the fault. At the same time the T172S line tripped single-end at Hartford Ave. At Hartford Ave. the S171S circuit breakers (CBs) and T172S CBs opened, at Drumrock the S171S CBs opened, and at Rise the S171S CBs opened. The S171S and T172S line CBs auto-reclosed after a time delay. The targets reported for the event are as follows:

- Hartford Ave – S171S DCB, T172S DCB TRIP AB;

- Drumrock – S171S DCB ZONE 1 A and B PH;
- Rise – S171S DTT.

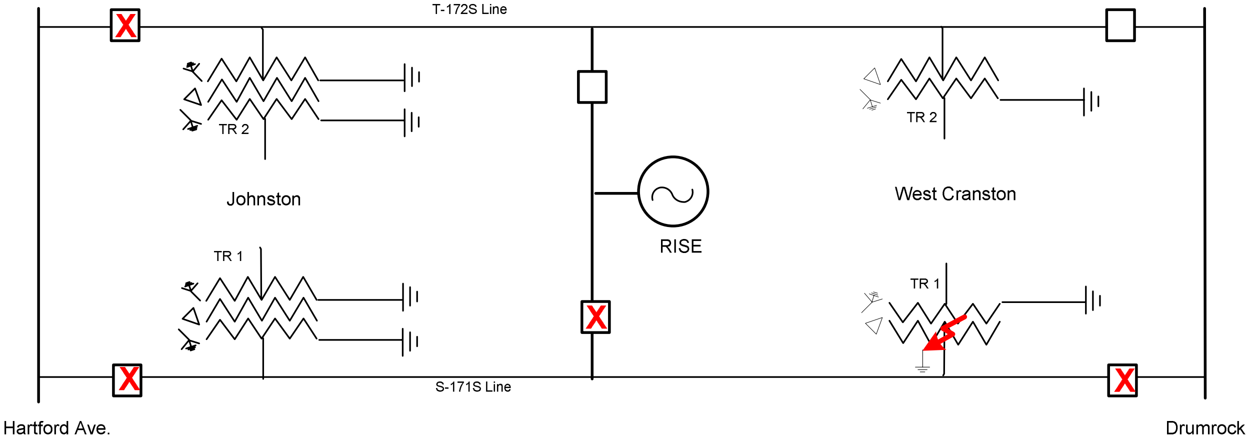
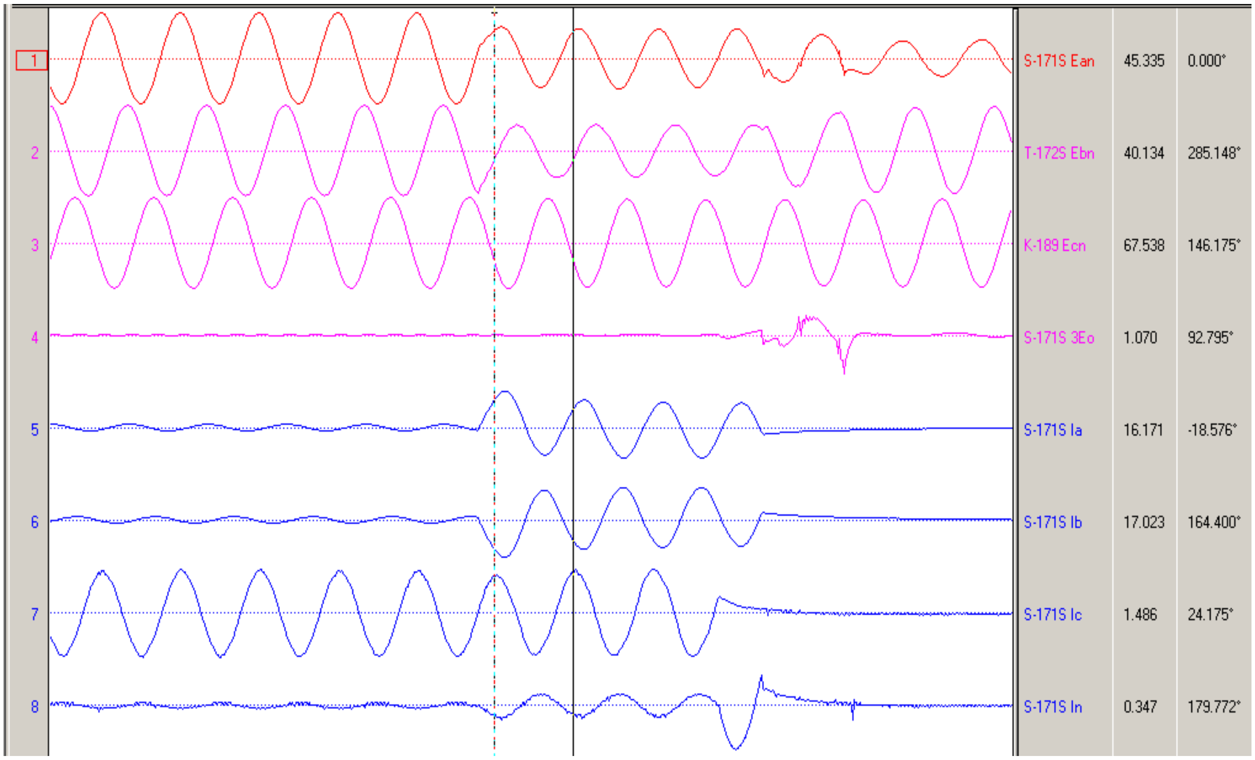


Figure 1 – One-line diagram S171S and T172S Lines

Analysis of the Drumrock event record (Figure 2) shows that an A to B phase fault occurred. Matching the terminal fault voltages and currents in the short circuit program for the known fault location suggests that the fault arc resistance was 0.8 primary ohms.



S-171S Ean	45.335	0.000°
T-172S Ebn	40.134	285.148°
K-189 Ecn	67.538	146.175°
S-171S 3Eo	1.070	92.795°
S-171S Ia	16.171	-18.576°
S-171S Ib	17.023	164.400°
S-171S Ic	1.486	24.175°
S-171S In	0.347	179.772°

Figure 2 – Fault Voltages and Currents at Drumrock Line S171S

The initial analysis of the event, using traditional methods determined that the S171S line operation was correct and the T172S operation at Hartford Ave was an over trip for the S171S line fault. The coordination check of the S171S and T172S Directional Comparison Blocking Scheme settings revealed that the T172S line DCB Zone 2 over reached the T172S reverse looking Zone 3 element at Rise resulting in no carrier blocking signal being sent from Rise allowing the trip of the T172S at Hartford Ave. Examination of the S171S and T172S line protection also revealed that the directional ground carrier start and trip elements were not set in the relays at Rise. Therefore, a review of the S171S and T172S DCB protection scheme settings was performed to correct the identified setting errors as part of this investigation and to determine if any other changes were required. A review of three terminal application criteria will be discussed in the next section prior to the discussion on the settings review.

THREE TERMINAL BLOCKING SCHEME SETTING CRITERIA [1, 2, 3]

A Directional Comparison Blocking (DCB) scheme utilizes Directional Distance (21) and directional ground over current (67N) relays with a pilot channel, typically Power Line Carrier On-off signal, to initiate high-speed tripping for line faults (Figure 3). Tripping is initiated if a local zone 2 over-reaching distance element or a directional ground over current element operates, and a remote-blocking signal is not received within a channel coordination time typically in the 16 to 50 ms range. For external system faults, reverse directional distance elements and ground over current elements are used to initiate the sending of the blocking signals. High-speed tripping is achieved at all terminals if the Zone 2 over reaching elements are set to detect internal and external line faults with all terminals in service, covering all possible infeed conditions. A Directional Blocking scheme offers the advantage of being dependable but, it is less secure. As a result, the blocking scheme is more likely to over trip for external faults should a communication failure occur.

21 Zone 1 - Non-communication instantaneous trip
21 Zone 2 - Communication aided trip and time delay back-up trip
21 Zone 3 - Reverse element blocks trip for external faults
67N Trip - Forward directional over current trip
67N Start - Reverse directional over current blocks trip for external faults

Figure 3 – Directional Comparison Blocking Scheme Elements

A transformer tapped on a line must be relayed if it provides positive or zero sequence fault current for line faults. This is called an “active” tap station and in effect makes the application a multi-terminal line. If the transformer has no positive sequence back feed, it does not need to be tripped and is called a “passive” tap station. If the transformer is an auto-transformer with a tertiary or, has a grounded wye-delta connection, it will increase ground relaying problems regardless of whether it is an active or passive tap station.

The directional distance Zone 1 reach is typically set to reach 85-percent of the actual impedance of the protected line for the shortest line length (lowest impedance) without in-feed. An alternative for multi-terminal lines is to set Zone 1 reach for 90-percent of the lowest apparent impedance at any tap for cases where there may be out-feed. It is desirable that the Zone 1 reach extend beyond the tee-point of the line from each terminal to permit high speed tripping without the need for communications with all terminals in service. This is because the in-feed will cause the Zone 1 element to under-reach at a given terminal. This can be a challenge for multi-terminal lines where the branches are of unequal length and may result with a section of the line where a fault will be undetectable by the Zone 1 relay.

The directional distance Zone 2 element is typically set to reach 200-percent of the actual impedance of the protected line with all terminals in service to provide sufficient sensitivity to detect all faults. An alternative method for setting the Zone 2 element is to set the reach to 125-percent of the apparent impedance for a fault at the remote terminal. The Zone 2 element is also configured to provide time delayed back-up protection. The time delay is set to coordinate with the directional distance Zone 1 protection of adjacent lines. The Zone 2 element must be set so that it does not overreach the Zone 1 protection of adjacent lines without any in-feed.

The directional distance reverse Zone 3 element is typically set equal to the remote terminal Zone 2 reach for a two terminal line to ensure that the Zone 2 element of the remote terminal does not over reach the reverse looking Zone 3. This will provide proper coordination by allowing a carrier start to be initiated, and thus block tripping of the protection scheme for external faults. The Zone 3 reach may need to be increased for multi-terminal applications. An alternate method is to use 130-percent of the apparent impedance used to calculate the remote terminal Zone 2 reach.

The DCB scheme utilizes two instantaneous directional ground over current relays. One to initiate a carrier start (block) and the second to initiate a communication aided trip. The directional ground start element is set sensitive enough to detect faults external to the protected line. The directional ground trip element is set to at least two times the directional ground carrier start element. The directional ground trip element may need to be set higher due to tapped load on the protected line. In addition a directional ground time over current relay is typically used as back-up protection. All directional ground time over-current relays must be set to coordinate without infeed conditions.

SETTINGS REVIEW [1, 2, 3]

The three-terminal application in this case study has all the elements of a multi-terminal line in the previous section. The S171S and T172S lines run parallel with a tapped source, creating branches that are of unequal length and the two lines are mutually coupled. The transformers at Johnston are 3-winding grounded wye-delta-wye, making this tap an active source which provides positive and zero sequence currents for faults. The transformer actually makes a fourth terminal on the line. The transformers at West Cranston are considered a passive tap as they do not contribute positive or zero sequence currents for faults on either of the lines. The S171S and T172S lines were originally a two-terminal application, with the tapped transformers at Johnston and West Cranston. When Rise was added as a tap, an additional complication for setting the relays arose because a newer generation microprocessor relay from a different manufacturer was used. The challenge is that the settings nomenclature and parameters of the two relays are moderately different requiring a thorough understanding of both manufacturers' products to properly set the relays for a three-terminal application. The transformers at Johnston present a fourth terminal, however, in the initial two-terminal design a compromise was made to use directional over current and ground protection to clear the low side at Johnston for line faults, which was not changed for the new three-terminal application. Construction of the S171S and T172S lines is similar, with the line impedance parameters almost identical, therefore, the same impedance data in Table 1 was used in the calculation of the settings for the DCB protection schemes for both lines.

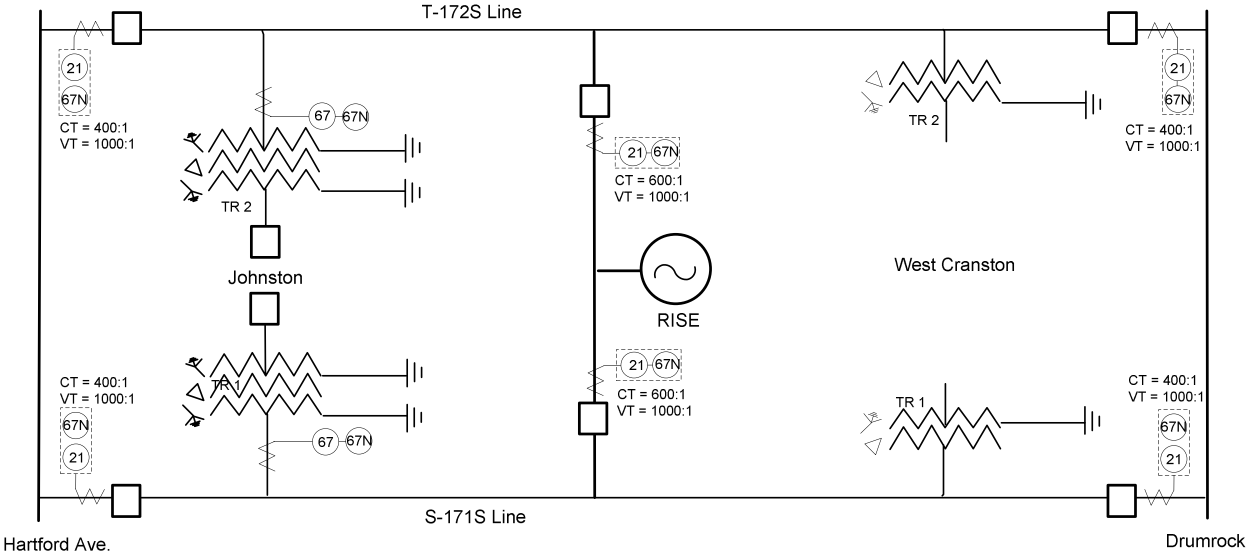


Figure 4 – S171S and T172S One-Line Diagram with Protection Configuration

Table 1

LINE IMPEDANCE DATA (PRIMARY VALUES)

	POSITIVE SEQ.	**ZERO SEQ**
HARTFORD AVE to DRUMROCK	7.61 @ 81 deg.	26.85 @ 72 deg.
HARTFORD AVE to RISE	1.99 @ 82 deg.	6.94 @ 72 deg.
RISE to DRUMROCK	5.90 @ 81 deg.	20.67 @ 72 deg.

Table 2

APPARENT IMPEDANCE DATA (Ohms-Pri.)

DRUMROCK (Fault at Hartford Ave.)	11.23 @ 78.5 deg.
HARTFORD AVE.(Fault at Drumrock)	10.41 @ 79.7 deg.
RISE (Fault at Drumrock)	14.55 @ 84.6 deg.
RISE (Fault at Hartford Ave.)	3.21 @ 84.2 deg.

Distance Element Settings

Protective relay guidelines recommend using apparent impedance for multi-terminal line applications (Figure 4). However, the application of relay settings is an art and science, therefore, in the setting of the distance elements the actual line impedance and apparent impedance have been used based on engineering judgment. The line impedance and apparent impedance data used for the following settings calculations are contained in Tables 1 and 2 above.

The Zone 1 distance element is typically set to reach 85-percent of the line for the shortest line segment (smallest impedance) with one terminal out of service, or as recommended for this configuration, the smallest apparent impedance. Comparing Table 1 and 2 above it is noted that the shortest actual line impedance for the Hartford Ave to Rise segment is 1.99 ohms-primary, and the apparent impedance for this line segment is 3.21 ohms-primary. Since the apparent impedance with all terminals in-service is larger than the actual line impedance for the shortest line segment, it was decided to set the Zone 1 relays at $0.85*Z_{\text{line actual}}$ of the lowest impedance for each terminal to prevent Zone 1 from over reaching either terminal when the Drumrock terminal is out-of-service. The same philosophy was used for the Zone 1 reach from Drumrock, where the actual line impedance of 5.9 ohms-primary was used. The settings are summarized in Table 3 below. With all terminals in service, Zone 1 will under-reach because of the infeed from the other terminal. The result is that a section of the line may not be protected by Zone 1 and reliance for fault clearing is on high-speed tripping by the Zone 2 communication aided trip for the line segment.

The Zone 2 reach is typically set for two times the actual line impedance of the longest line segment, or as recommended for this configuration, is set for 1.2 times the apparent impedance of the longest line segment out of each terminal. Comparing the line impedance data in Table 1 with the apparent impedance data in Table 2 it can be noted that the apparent impedance is much larger than the actual line impedance, therefore the Zone 2 reach was set at $1.2*Z_{\text{apparent}}$ of the longest line section (largest impedance) from each terminal. The settings are summarized in Table 3 below.

Table 3

	HARTFORD AVE			**RISE**			**DRUMROCK**		
RATIOS	CT: 400	VT: 1000	RATIOS	CT: 600	VT: 1000	RATIOS	CT: 400	VT: 1000	
	AS FOUND	**AS LEFT**		**AS FOUND**	**AS LEFT**		**AS FOUND**	**AS LEFT**	**SCALE**
Z1	0.73	0.73	Z1	1.26	1	Z1	2.26	2	ohms-sec
Z2 (TRIP)	7.88	5.4	Z2 (TRIP)	6.44	10.5	Z2 (TRIP)	6.36	6.36	ohms-sec
Z3 (START)	7.88	10	Z3 (START)	6.44	24	Z3 (START)	6.36	10	ohms-sec
CDG (TRIP)	4	4	CDG (TRIP)	Not Set	2	CDG (TRIP)	3	3	amps
CDG (START)	0.25	0.25	CDG (START)	Not Set	0.2	CDG (START)	0.25	0.25	amps
COORD TMR	11	21	COORD TMR	12.5	20.8	COORD TMR	11	21	mS

The Zone 3 element in a directional carrier blocking scheme being reversed in order to initiate a block for external faults is typically set at 1.3 times the Zone 2 reach of the remote terminal protection for the highest impedance to ensure that the Zone 2 (carrier trip) does not over reach the Zone 3 reverse (carrier start) in order to prevent over trips. When running the traditional short circuit simulation it was noted that for the Rise terminal, the Zone 3 reverse elements did not reach far enough to initiate a block signal for faults near West Cranston. The Zone 3 reverse element settings at Rise were increased to 24 ohms secondary (40 ohms primary) to ensure that the blocking signal would be initiated for external faults up to the transformers at West Cranston. Based on the simulation, the Hartford Ave and Drumrock reverse settings would also block for external faults up to the transformer at Johnston and West Cranston respectively. The Zone 3 settings are summarized in Table 3.

Directional Ground (DG) Settings

In this application the DG Start element is set at 100 amps primary at Hartford Avenue and Drumrock, and 120 amps primary at Rise to achieve a high sensitivity for detecting external faults. The Directional Ground Carrier Trip is set at a minimum of three times the Directional Ground Carrier Start element for multi-terminal lines. However, for this application the DG trip elements are set higher than the typical three times the DG start element to prevent over tripping for faults on the low side of the 3-winding transformers at Johnston. The settings are summarized in Table 3.

Carrier Coordination

The coordination time delay was increased to 21 ms (1.25 cycles) from 11 ms to allow for better coordination of carrier block signals received. The 1.25 cycle coordination time is derived based on relay manufacturer recommendations to set the coordination timers for one cycle plus the channel delay.

Some of the reach settings in Table 3 will not match the criteria discussed above exactly. The reason for this is that some of the existing settings were close enough to the actual calculated values that a setting change for that element was considered not needed. The other exception is the Zone 3 reverse element at Drumrock, where during the settings review process a judgment was made to set the Zone 3 reverse element identical to the Zone 3 reverse element at Hartford Ave. A coordination check based on the settings in the table verified that the protection would function properly based on these settings.

METHODS FOR VERIFICATION OF RELAY SETTINGS

End-to-End Testing [4]

National Grid periodically utilizes end-to-end testing to verify the protection system functions properly for specific fault conditions, in particular when a protection scheme has operated improperly during a power system fault. Ideally the conditions of the fault will be replayed from fault records retrieved from the event through a satellite synchronized relay test set. For operations where fault records are not available, a power system model for short circuit simulations is used to generate the COMTRADE records for simulated events for playback through the protective relays. Typically a series of tests involving both internal and external faults are created to verify the protection scheme operates as expected. Also, in the case where the protection system operates improperly for a known system fault, that operation will be simulated providing the fault location is known.

End-to-end testing to verify protection scheme settings and operation is a valuable tool to employ not only for protection system mis-operations, but commissioning and maintenance testing as well. However, there may be times where end-to-end testing may not be used because of difficulty in scheduling an outage. This is where good simulation tools can aid the engineer to determine if the protection schemes will operate properly. The engineer should use these simulation tools regardless of whether end-to-end testing is performed or not.

Protection Simulation

The protection simulation environment allows a user to compute settings and send them to a relay, or to read settings from a relay and test them in the modeled system. It is obvious from references [5 to 12] that every manufacturer has a different approach to relay design, so it is imperative that the relay manufacturer's exact operating equations and operating criteria be used when determining how a relay performs under different power system conditions. The components of a typical simulation environment are:

- A network model (buses, generators, lines, shunts, and transformers) and a short-circuit analysis with high-level commands for faults and outage contingencies [13]. Currents and voltages are treated as steady-state phasors.

- A library of detailed relay models [14]. A relay model consists of instantaneous overcurrent, time overcurrent, directional, distance, voltage, timer, and recloser elements, with auxiliary elements for internal logic and pilot (teleprotection) schemes. Special code for each relay model interprets the setting names and evaluates the comparators using a steady-state phasor analysis [15]. As a result, element response is always based on the actual relay logic. Actual settings are modeled so that the relay model is "set" in the same way as the physical device.

- Rules for locating relays. An integrated database [16], with an interactive editor, contains the CTs and VTs connecting the relays to the network, and specifies the protected equipment and its logical breakers.

- A macro facility. The macro language has many commands associated with a high-level language, such as IF-THEN-ELSE, DOWHILE, and DO loops tailored to power system applications. The macro language has been successfully applied to develop algorithms for automatically setting distance and overcurrent relays based on utility-specific rules [17, 18].

- Tools for wide area coordination. The macro language also makes it possible to perform wide-area coordination studies. As described in [19], an automated procedure was used to evaluate relay coordination in an extensive part of the utility's 220kV and 400kV networks. The authors argue that considering the huge investment in power system assets, it only makes sense to equip utilities with tools that enable automatic detection of lack of coordination and provide assistance with the adjustments needed to resolve them.

- Import/export facilities to communicate with a physical relay indirectly via relay vendor databases, or to send settings to a field engineer. Most numerical relays have their own setting software and can store relay settings in a database. The independent simulation environment complements this by modeling together the entire network and its protective devices from multiple vendors. Settings can then be transferred to the relay vendor's database product for subsequent electronic transmittal to the relay, making paper setting sheets unnecessary.

Coordination check with the original settings

The relay settings that were in place at the time of the incident were entered into the software models of the relays in the National Grid short-circuit model. The DCB scheme was also modeled and simulated on both the S171S and T172S lines.

One of the key causes of the over-tripping of the T172S line at Hartford Avenue was the failure of the reverse-looking carrier start element at the Rise terminal to detect the external fault at West Cranston (on S171S). This allowed the DCB scheme at Hartford Avenue (on T172S) to operate.

As a first test, the 0.8Ω A-B fault was applied at the West Cranston tap to see if the cause of non-operation of the Rise carrier-start element could be determined. Figure 5 shows the circular mho characteristics of three relevant elements: (1) the over-reaching zone 2 element at Hartford Avenue on T172S, (2) the under-reaching zone 1 element at Drumrock (on S171S) and (3) the carrier start element at Rise (on T172S).

The T172S and the S171S lines are laid out end-to-end, with the Hartford Avenue bus at both the origin of the R-X plane, and further into the R-X plane. The first branch seen is T172S to Drumrock; the next branch is the S171S line laid out from Drumrock back to Hartford Avenue.

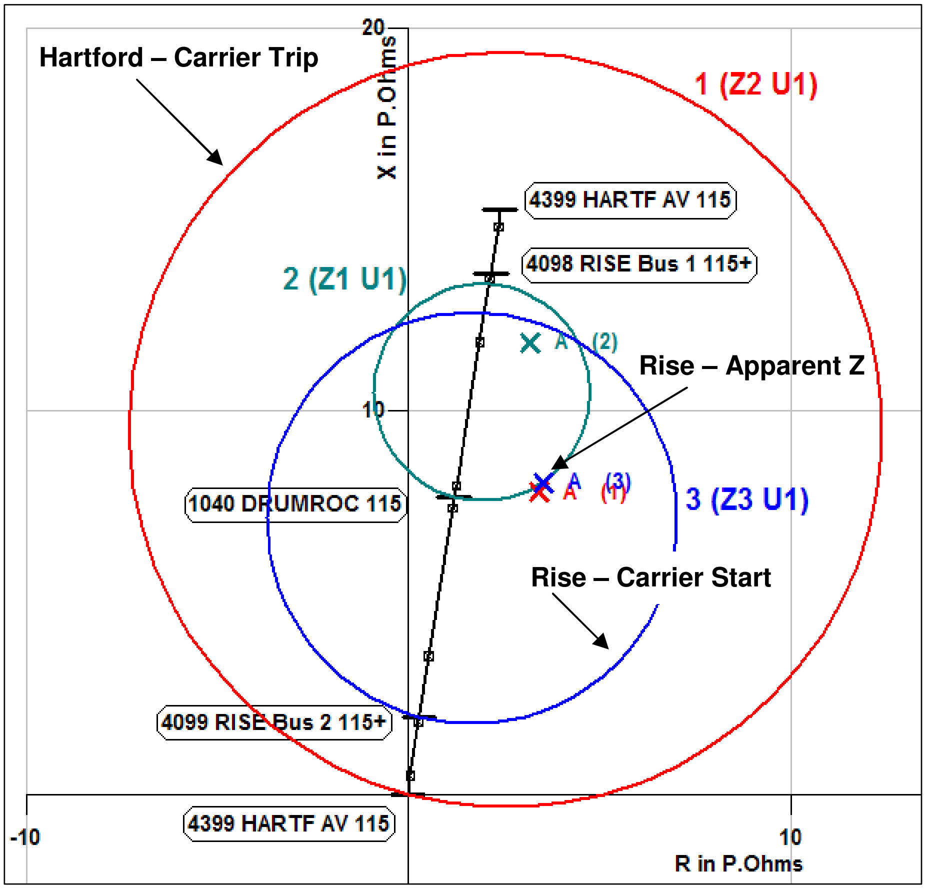
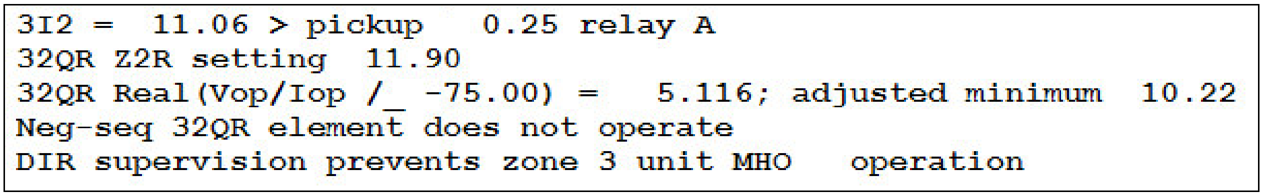


Figure 5: R-X diagram showing the T172S and S171S lines

In Figure 5 the R-X diagram shows the T172S and S171S lines, laid out end-to-end. Curve 1 (red) is the over-reaching zone 2 element at Hartford Avenue on T172S. Curve 2 (light-green) is the under-reaching zone 1 element at Drumrock on S171S. Curve 3 (blue) is the reverse-looking carrier start element at Rise (on T172S).

Notice that the apparent impedance (as shown by X marks) for the zone 2 element at Hartford Avenue and the carrier start element at Rise are quite close to each other. Since the apparent impedance plots inside the characteristic of the carrier start element at Rise, we expect it would operate and transmit a blocking signal to the Hartford Avenue and Drumrock ends.

But this did not happen. The Rise relay uses a negative-sequence impedance based directional element that was not set correctly. It prevented the carrier start element from operating. Figure 6 shows an extract from the detailed element report as generated by the simulation tool.



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3I2 =   11.06 > pickup   0.25 relay A
32QR Z2R setting  11.90
32QR Real(Vop/Iop /_ -75.00) =   5.116; adjusted minimum  10.22
Neg-seq 32QR element does not operate
DIR supervision prevents zone 3 unit MHO   operation
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Figure 6 – Negative-sequence directional element report from the simulation tool

The report from the simulation tool (Figure 6) shows that the impedance-based negative-sequence element has a setting of 11.90Ω (secondary). The actual operational threshold is computed from the setting, and the measured voltage and current; the threshold in this case is 10.22Ω. The measured negative-sequence source impedance is 5.116Ω. Since the measured source impedance is less than the computed threshold, the negative-sequence element does not operate. The setting of 11.90Ω clearly prevents the operation of the carrier start element at Rise.

Since no blocking signal was received at Hartford Avenue, that terminal tripped once the coordinating timer elapsed. Figure 7 shows this condition. Again, the simulation tool was used to perform the sequential tripping scenario.

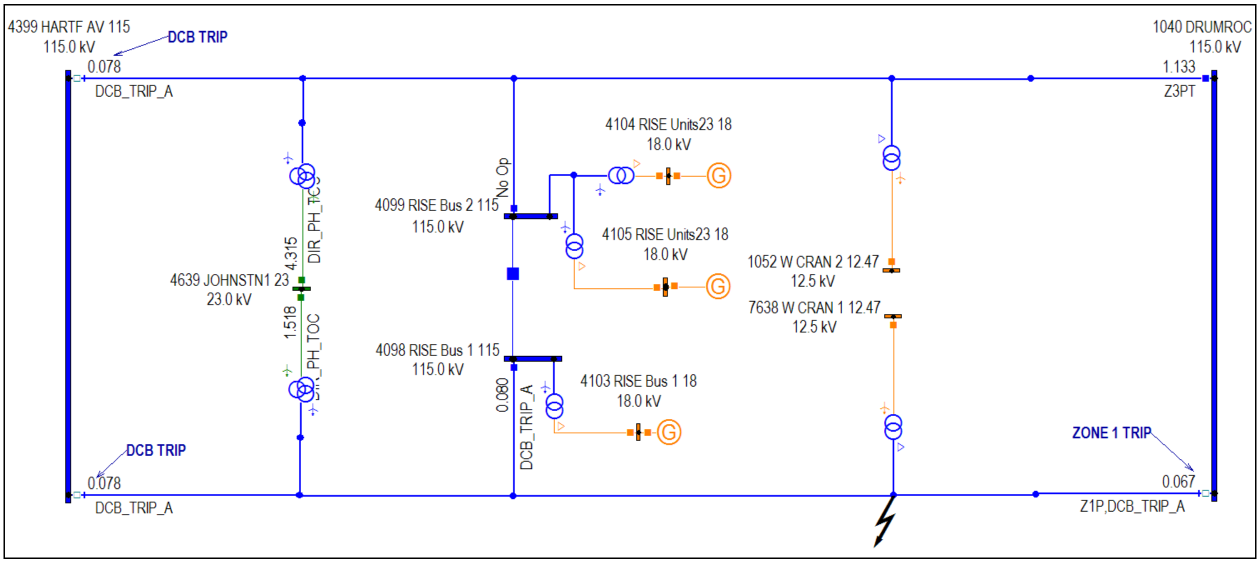

Figure 7 - Sequential tripping simulation.

Figure 7 shows that the circuit breaker at Drumrock (on S171S) opened at 0.067s. A zone 1 element issued the trip signal. At Hartford Avenue, communication assisted tripping results in the circuit breakers on both T172S (over-trip) and S171S (correct trip) to open at 0.078s.

Although not shown in Figure 5, the reverse element at Drumrock on T172S did not detect the fault at West Cranston as a reverse fault. In fact, the fault appeared to the relay as a forward fault, but beyond the zone 2 reach. This is why Figure 7 shows a predicted zone 3 forward time-delayed operation at Drumrock.

Coordination check with new settings

After a thorough analysis and review of the event, new relay settings were computed, including those for the impedance-based negative-sequence directional element. With these settings in place, the same scenario was studied both in the R-X plane and by the sequential stepped-event method. Figure 8 shows the results of the sequential tripping simulation.

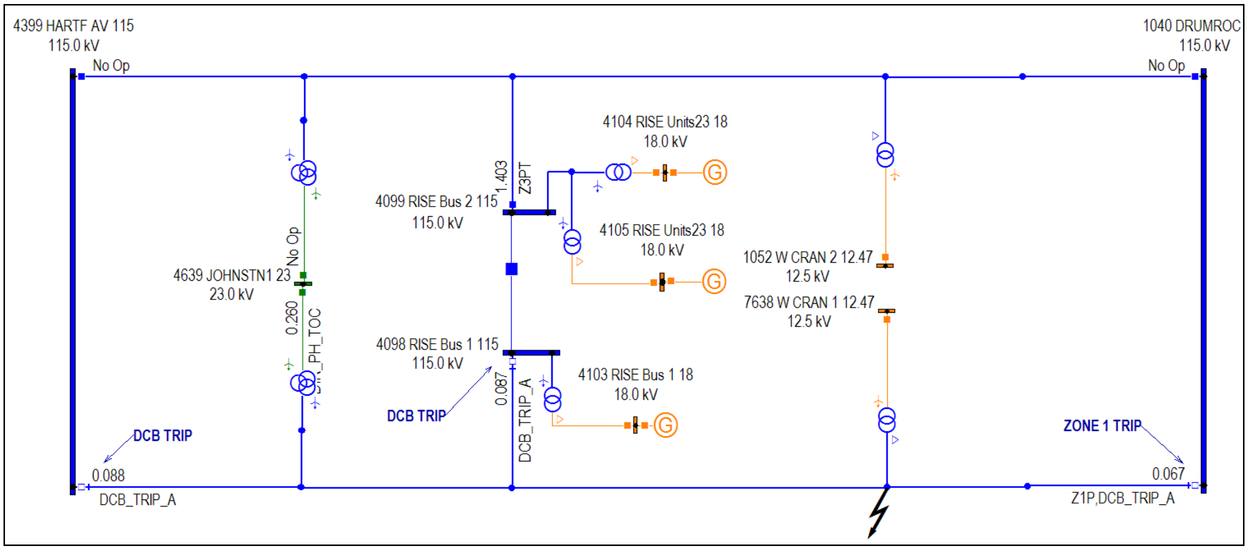

Figure 8: Sequential tripping simulation with new settings.

At Drumrock (on S171S) the zone 1 element operated and caused the circuit breaker to open at 0.067s. At Hartford Avenue and Rise, communication assisted tripping is seen. No operation is predicted at Hartford Avenue or Drumrock on T172S.

Figures 7 and 8 show only the highlights of the tripping sequence. The entire tripping sequence for both the scenarios (old and new settings) can be found in the appendix.

This example underscores the importance of the following to a relay engineer [20]:

- A network model with accurate representation of transmission lines, generators, transformers, and other components, in both the positive- and zero-sequence networks.
- Ability to model protective devices from different vendors in full detail, so that the actual comparator equations, and internal logic, to the extent possible in a phasor-based environment, can be considered.
- Ability to model the protection system as an entity, rather than just as individual protective devices working by themselves. This will allow uncovering communication scheme issues, and other problems that might arise after the first circuit breaker has opened.
- Ability to perform periodic wide-area coordination and sensitivity reviews. This ensures that as the system changes, and new settings are computed, overall coordination objectives are still being met.

With such simulation tools in hand, the protection engineer can gain a high degree of confidence that the settings he or she has computed will work well in the field. It is not possible to protect against all possible scenarios, but most of the obvious problem areas can be addressed.

CONCLUSIONS

The over trip for the three-terminal directional comparison blocking (DCB) scheme was due to improperly applied settings that were avoidable. A thorough understanding of the protection scheme applications alone will not eliminate all human error events. The protection engineer must perform a thorough evaluation of the protection scheme settings using the tools available today.

The initial event analysis determined that the T172S line DCB protection scheme Zone 2 element at Hartford Avenue over reached the Zone 3 reverse looking element on the T172S line DCB protection at Rise. This was clear from looking at the impedance characteristics of the various elements in the R-X plane, and by performing short-circuit studies for faults near the West Cranston tap, toward Drumrock. The reach of the reverse zone 3 element at Rise was therefore increased to 24Ω (secondary) from its initial setting of 6.44Ω (secondary). This was not the only setting change that was performed. A full review of all the settings on all the relays on both S171S and T172S was undertaken. Based on extensive short-circuit studies, new settings were computed and entered into the relays.

During computer simulation studies with the original and new settings, an issue emerged, which although small, has a significant impact. For an A-B fault with 0.8Ω (primary) fault resistance at the West Cranston tap, the apparent impedance measured by the over-reaching zone 2 element at Hartford Avenue (on T172S) was very close to the apparent impedance measured by the reverse carrier start zone 3 element at Rise, and within their respective characteristics, as shown in Figure 5. But, the reverse zone 3 element did not operate, and this was due to the rather high setting on the supervising negative-sequence directional element. It prevented the zone 3 element from operating, which in turn did not generate a blocking signal. Thus, while over-reach of the zone 2 element at Hartford Avenue beyond the reverse zone 3 element at Rise was a problem, it was not the only factor that caused the over tripping event.

With the recalculated settings, and increased reaches for the reverse (carrier start) elements, simulations in the R-X plane showed proper operation of the carrier start element at Rise.

To gain further confidence in the settings, the DCB scheme was modeled as part of the simulation tool, on both the S171S and T172S lines. With the scheme in place, simulation results show no over-tripping on T172S for the fault at West Cranston. Simulations with other fault types and at different locations also showed no unwanted relay operations.

To effectively use simulation tools it is imperative that the tool models the behavior of the protective relays to match as closely as possible, the protection algorithms and logic employed by the actual relay. Further, it must be possible to simulate and test the protection system, rather than just individual relays. This will give the protection engineer a high degree of confidence that the settings are applied correctly.

The protection engineer should also perform periodic evaluation of the protection system to check setting sensitivity and coordination, and make adjustments. This ensures that the protective relay settings continue to perform adequately in the face of changes to the power system.

End-to-end testing in the field is a good final check, especially with communication aided protection schemes, as it verifies the complete system performance. But it may not always be possible to schedule an outage of an in-service transmission line. Then, the engineer has to rely on simulation tools.

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BIOGRAPHIES

Jeffrey Pond, National Grid

Jeffrey Pond joined National Grid in 1980. He is a Senior Engineer in the Protection Standards and Support Department, where he is responsible for the analysis of Transmission and Distribution system disturbances. He is also responsible for the selection, configuration and maintenance of disturbance monitoring equipment. Previously Jeff worked for the Substation Integration Team, and the Relay and Telecommunications Operations Group. He received an Associate degree in Electrical Engineering Technology from Wentworth Institute of Technology, in Boston, MA, a BS in Business Management from Lesley University in Cambridge, MA, and a MS in Power Systems Management from Worcester Polytechnic Institute in Worcester, MA. He is a registered Professional Engineer in the Commonwealth of Massachusetts, is a senior member of IEEE, and is a member of the Main Committee of the IEEE Power System Relaying Committee.

Ashok Gopalakrishnan, Electrocon International Inc.

Ashok Gopalakrishnan joined Electrocon in May 1999. He is involved in the development of digital relay models, breaker duty functions and other protection and coordination tools for use in the Computer Aided Protection Engineering (CAPE) package. He is a graduate of the Birla Institute of Technology and Science, Pilani, India, and Texas A & M University, College Station, Texas. Ashok is a member of the IEEE.

Tony Giuliante, ATG Consulting

A.T. Giuliante is president and founder of ATG Consulting (previously ATG Exodus). Prior to forming his company in 1995, Tony was Executive Vice President of GEC ALSTHOM T&D Inc. - Protection and Control Division, which he started in 1983. From 1967 to 1983, he was employed by General Electric and ASEA. In 1994, Tony was elected a Fellow of IEEE for "contributions to protective relaying education and their analysis in operational environments." He has authored over 50 technical papers and is a frequent lecturer on all aspects of protective relaying, including electromechanical, solid state and digital based equipment. Tony is a past Chairman of the IEEE Power System Relaying Committee 1993-1994, and past Chairman of the Relay Practices Subcommittee. He has degrees of BSEE and MSEE from Drexel University 1967 and 1969.

APPENDIX

The individual breaker openings that led to eventual clearing of the A-B 0.8Ω fault are presented here.

Fault clearing with original settings

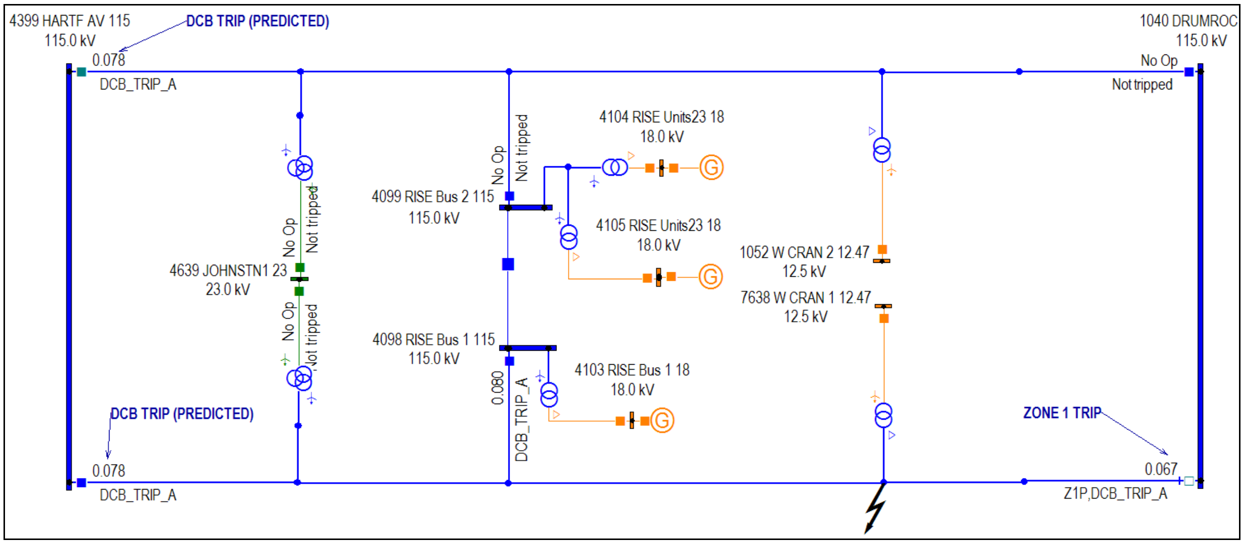

Figure 9 - Event 1: Circuit breaker at Drumrock on S171S opens at 0.067s

Operation of the zone 1 phase distance element at Drumrock (S171S) causes the circuit breaker there to open at 0.067s. Communication assisted breaker operation at 0.078s is predicted at Hartford Avenue on both S171S and T172S. In fact, the breakers are already opening at this point.

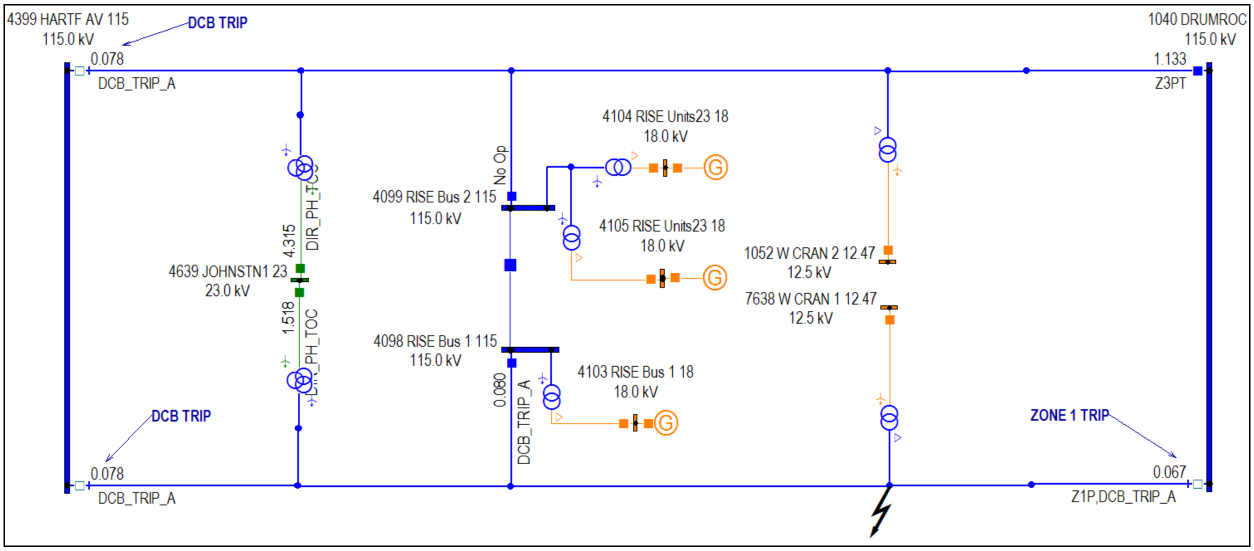

Figure 10 - Event 2: DCB Trip at Hartford Avenue on both S171S and T172S

At Hartford, circuit breakers on both S171S and T172S open at 0.078s.

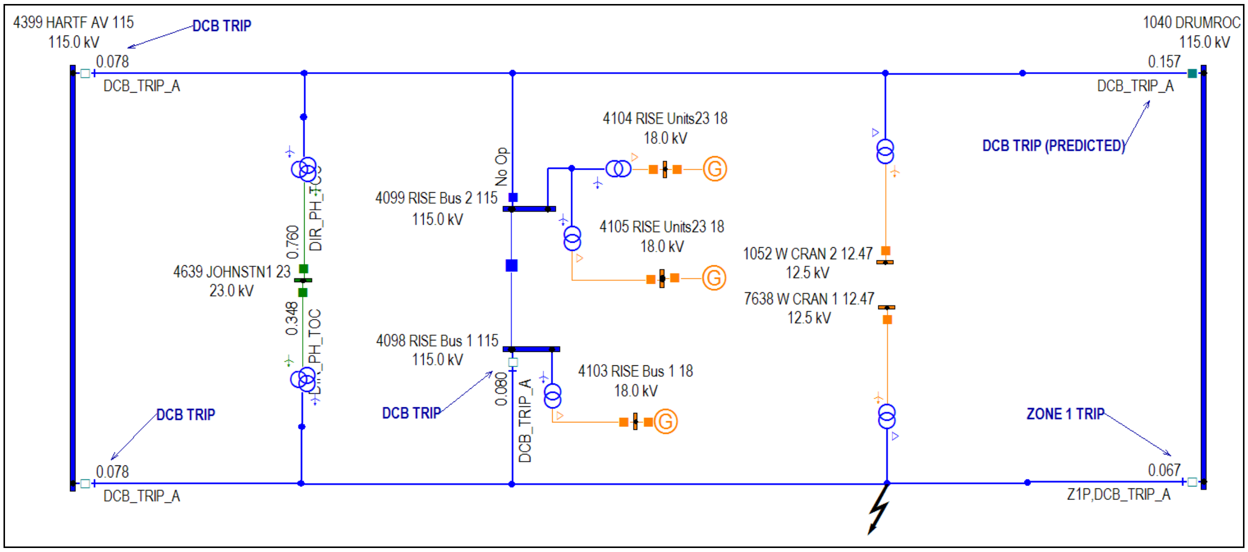

Figure 11 - Event 3: DCB Trip at Rise on S171S

The breaker at Rise (S171S) opens at 0.08s, due to a trip signal from the DCB scheme. Also, note that at Drumrock on T172S, DCB tripping is predicted, but this is at least 0.07s (4.2 cycles) in the future. The over-reaching zone 2 at Drumrock will drop-out in the next event.

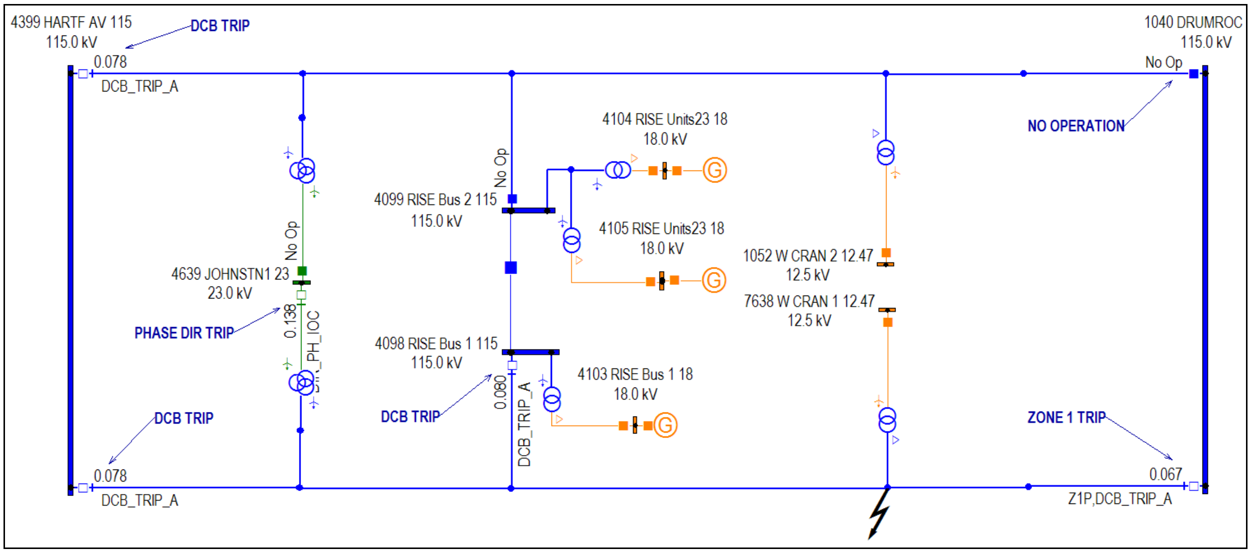

Figure 12 - Event 4: Phase directional trip at tapped transformer

The phase directional relays on the low-side of the tapped transformer operate and open the low-side breaker at 0.138s. Also note that no operation of any kind is predicted at Drumrock (T172S). The fault is now cleared.

Fault clearing with new settings

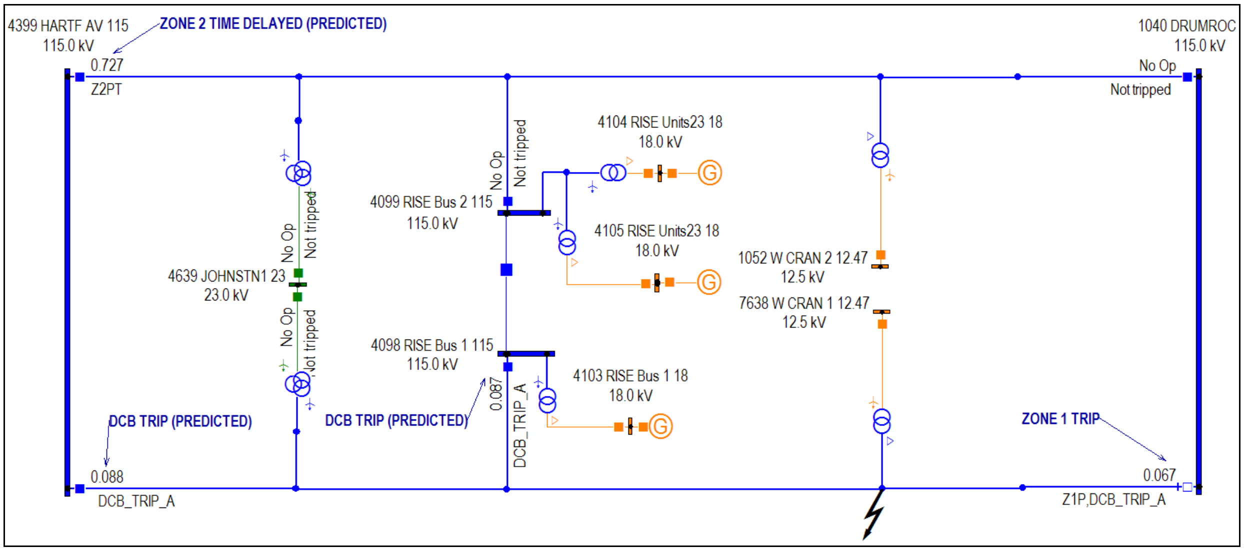

Figure 13 - Event 1: Circuit breaker at Drumrock on S171S opens at 0.067s

As before, the first circuit breaker to open is the one at Drumrock on S171S. A zone 1 element issued the trip signal. Communication-assisted DCB tripping is predicted at Rise and Hartford Avenue, both on S171S. At Hartford Avenue on T172S, circuit breaker opening is predicted only at 0.727s, due a time-delayed zone 2 operation. This means that a blocking signal was received from Rise, which successfully prevented any communication-assisted tripping at Hartford Avenue on T172S.

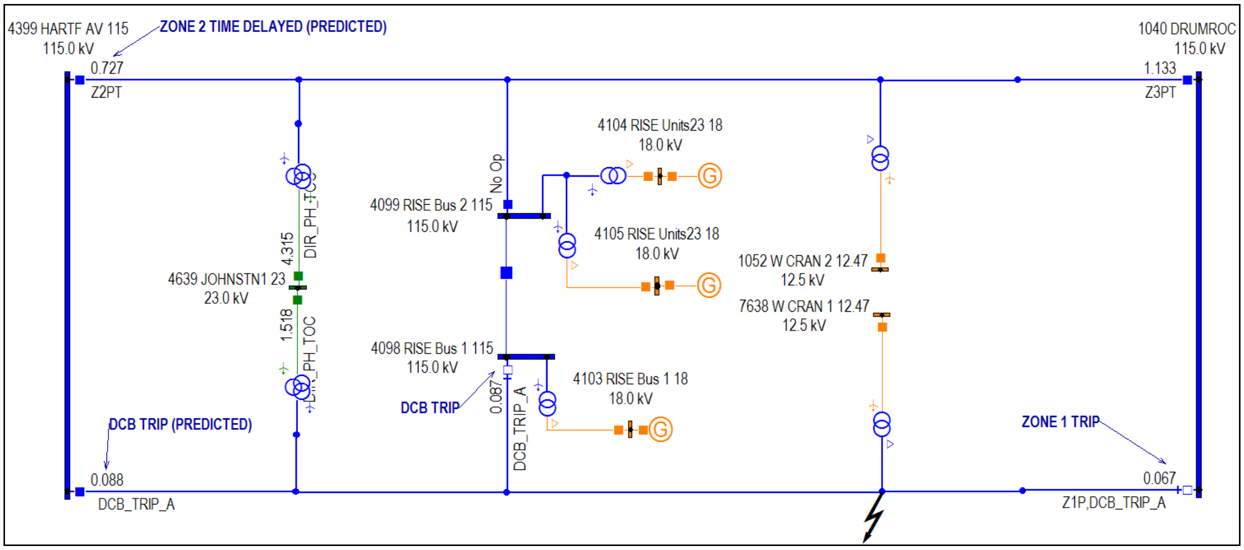

Figure 14 - Event 2: Circuit breaker at Rise (S171S) opens at 0.087s

The circuit breaker at Rise on S171S opens at 0.087s due to communication-assisted DCB trip.

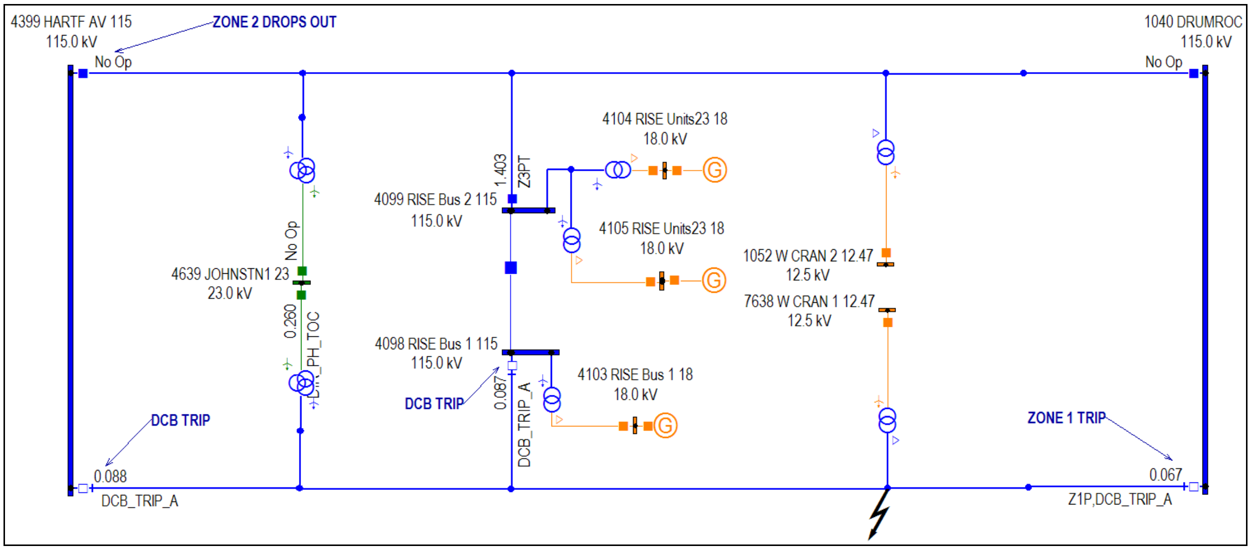

Figure 15 - Event 3: DCB trip at Hartford Avenue (S171S)

The circuit breaker at Hartford Avenue on S171S opens at 0.088s, due to communication-assisted tripping. Note that the zone 2 time-delayed trip at Hartford is no longer predicted. That element drops out once the breaker on S171S opens.

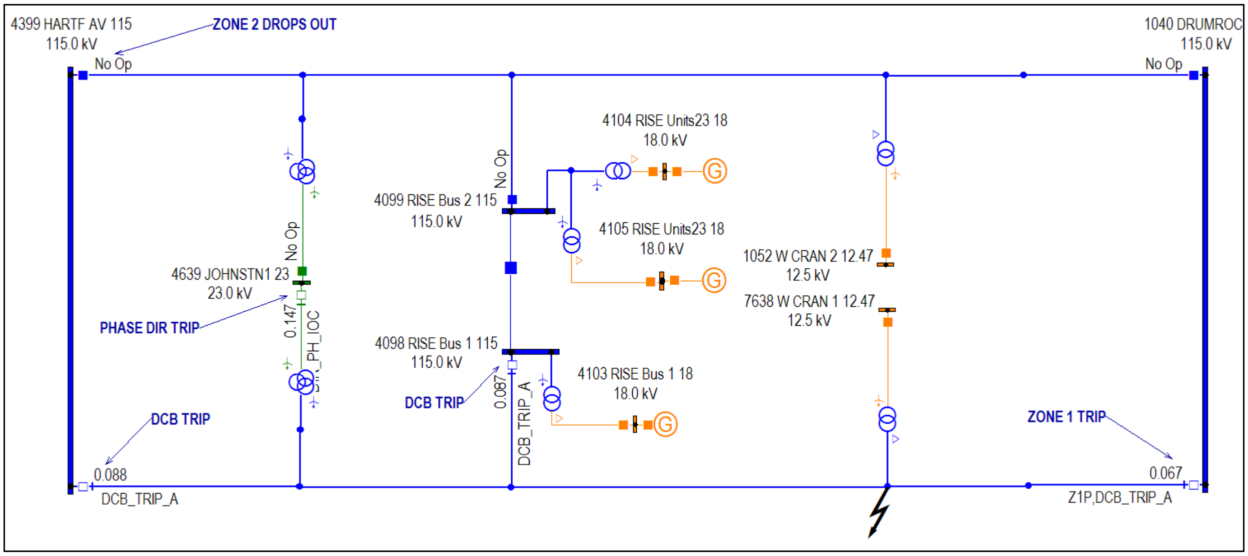

Figure 16 - Event 4: Phase directional trip at tapped transformer

The fault is cleared once the phase directional element on the low-side of the tapped transformer operates and opens the breaker. There is no over-tripping on any of the terminals of T172S.