Analysis of POTT Scheme Operation for an External Fault

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Introduction

A fault event occurred on a 115kV line that resulted in an unexpected operation of a parallel 345kV line. This paper presents an analysis of the event utilizing fault records, from digital fault recorders and relays, and short circuit simulation to determine what happened and why the 345kV line operated at one terminal for the external fault on the 115kV parallel line. The fault records captured by disturbance monitoring equipment and the short circuit simulation provided valuable analog and digital data which gave an insight into the nature of this disturbance allowing an efficient investigation and accurate diagnosis of the event.

Incident Summary

On January 11th, 2008, the national Grid Control Center reported that at 13:32:03 a lightning stroke caused a fault on the 115kV E157 Line between the Millbury and Northborough Road terminals. Simultaneously, the 345kV 313 Line operated at the Millbury terminal only. The Sequence of events are shown in Table 1 and the line configurations are shown in Figure 1. The E157 and 313 lines share a common right-of-way with three other lines. The Control Center reported that the 115kV E157 Line tripped and auto-closed correctly at both terminals, and the Millbury terminal of the 313 Line operated simultaneously to the E157 Line fault and auto-closed. Targets reported for this event are as follows:

- Northborough Road: E157 Permissive Overreaching Transfer Tripping (POTT)
  E157 Directional Distance Zone 1 C-Phase-to-Ground (DDZ1)

- Millbury: E157 Permissive Overreaching Transfer Tripping (POTT)
  E157 Directional Distance Zone 1 C-Phase-to-Ground (DDZ1)

  313 Permissive Overreaching Directional Ground (PODG) – Key POTT
  313 Permissive Overreaching Transfer Tripping (POTT)

Table 1 – Sequence of Events for 2008-01-11 Event

13:32:03.899	NRTHBORORD 115	E-157 OCB	OPEN
13:32:03.908	NRTHBORORD 115	57-60 OCB	OPEN
13:32:03.929	MILLBURY#3 345	1357 GCB	OPEN
13:32:03.929	MILLBURY#3 345	313 GCB	OPEN
13:32:04.059	MILLBURY 115	5765 OCB	OPEN
13:32:04.117	MILLBURY 115	5765-74 OCB	OPEN
13:32:09.274	MILLBURY 115	5765 OCB	CLOSE
13:32:09.330	MILLBURY#3 345	1357 GCB	CLOSE
13:32:14.098	NRTHBORORD 115	E-157 OCB	CLOSE
13:32:58.795	NRTHBORORD 115	57-60 OCB	CLOSE
13:33:13.805	MILLBURY#3 345	313 GCB	CLOSE
13:33:23.689	MILLBURY 115	5765-74 OCB	CLOSE

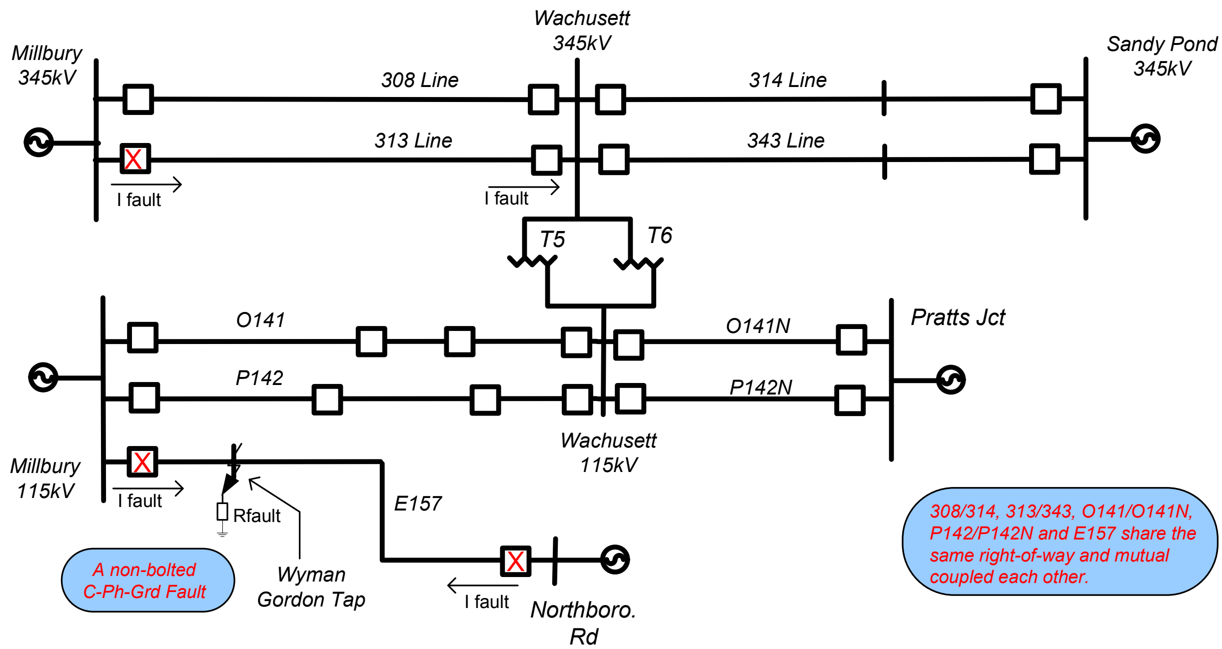

Figure 1. System One Line Diagram with E157 Line Fault

Investigation and Analysis

The first step of the investigation was to review relay targets, Sequence-of-Events (SOE), and fault records from the digital fault recorders (DFRs) and the E157 and 313 line relays at Millbury, Northborough Road and Wachusett substations. Based on the reported targets, the SOE (Table 1) and the fault records captured by the Millbury DFRs (Figure 2) it was confirmed that a C-phase-to-ground fault occurred on the E157 Line and the E157 Line Permissive Overreaching Transfer Trip (POTT) scheme operated correctly. Review of the same record showed that no fault had occurred on the 313 Line, however, there was significant neutral current present due to the effects of mutual coupling. Review of the targets, SOE, and DFR records confirmed that the 313 Line POTT scheme operated resulting in a single-end trip of the 313 Line at Millbury 3 only. It appeared that the 313 POTT scheme operated incorrectly for this event. The investigations focus moved to identify why the 313 POTT scheme operated for the E157 fault and why was the result only a single-ended trip?

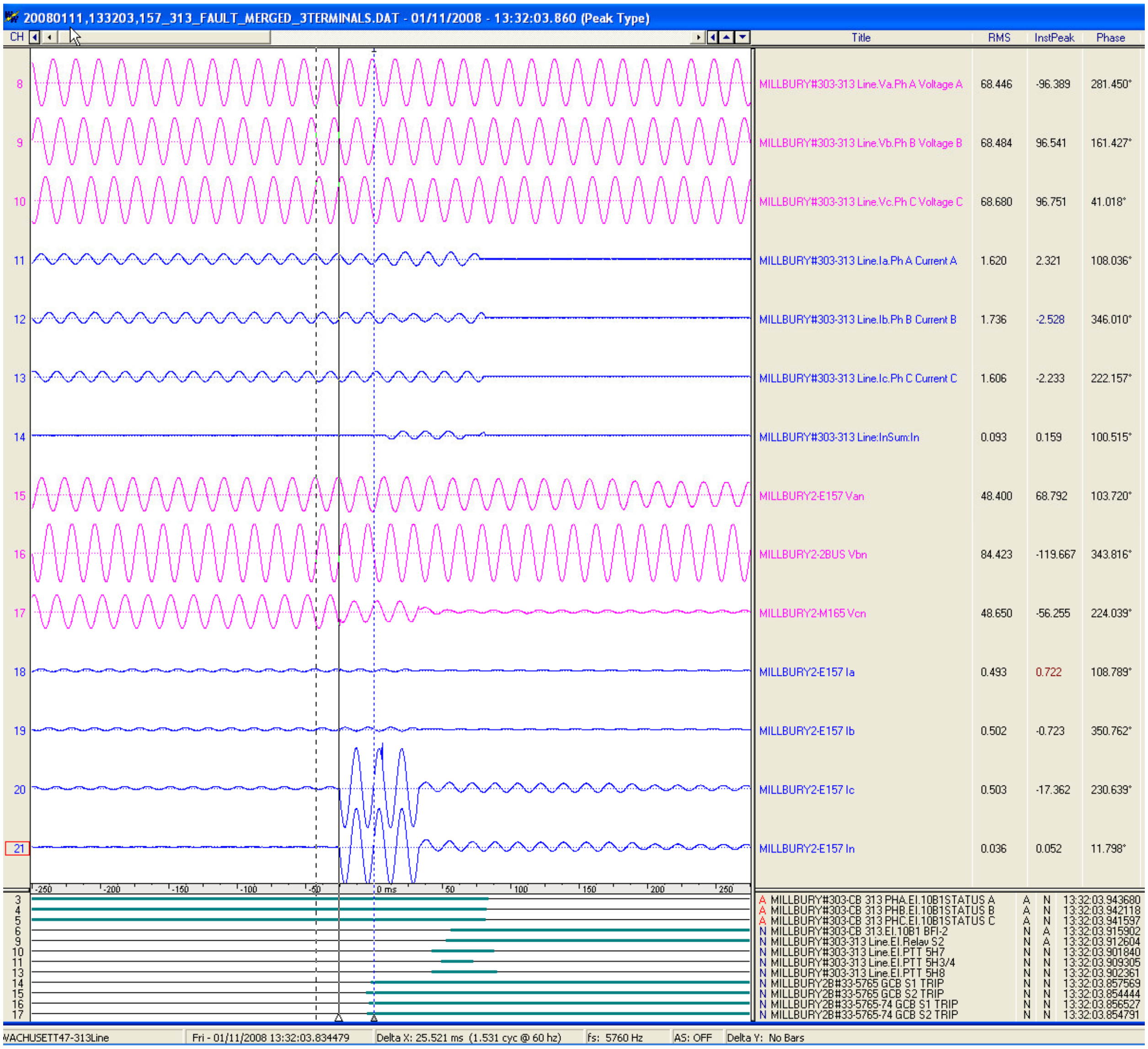

Figure 2. E157 and 313 Line DFR Waveforms at Millbury Substation at 13:32:03

NOTE: Millbury #303 313 Line PTT5H7 and PTT5H8 = 313 Line POTT SEND
Millbury #303 313 Line PTT5H3/4 = 313 Line POTT RECEIVE

The DFR records from the Millbury substations and Wachusett 47 were reviewed. Figure 3 is a merged file of the records from the three substations for the purpose of this discussion. Analysis revealed that the 313 POTT scheme sent permissive transfer trip from Wachusett. Wachusett also received POTT and POTT was sent from Millbury and received at Millbury. Unfortunately the Waveform from the Millbury 3 DFR did not line up with the waveforms from the Millbury 2 and Wachusett 47 DFRs. Before the investigation continued the reason for the error needed to be identified. After careful analysis it was determined that the timing error existed in all devices at Millbury 3. The DFR, relays and Remote Terminal Units at all three substations are time synchronized to a local GPS receiver, yet the Millbury 3 GPS receiver was 33 milliseconds faster. Since the error was consistent it was determined that the GPS receiver was the most likely cause of the error and before the analysis continued the time needed to be adjusted in the DFR and Relay records related to this event from Millbury 3. Figure 4 shows the DFR waveforms with Millbury 3 time adjusted. The time adjusted waveforms provide a better snapshot of what occurred during the event and it is clear that POTT was sent and received to allow a high-speed trip.

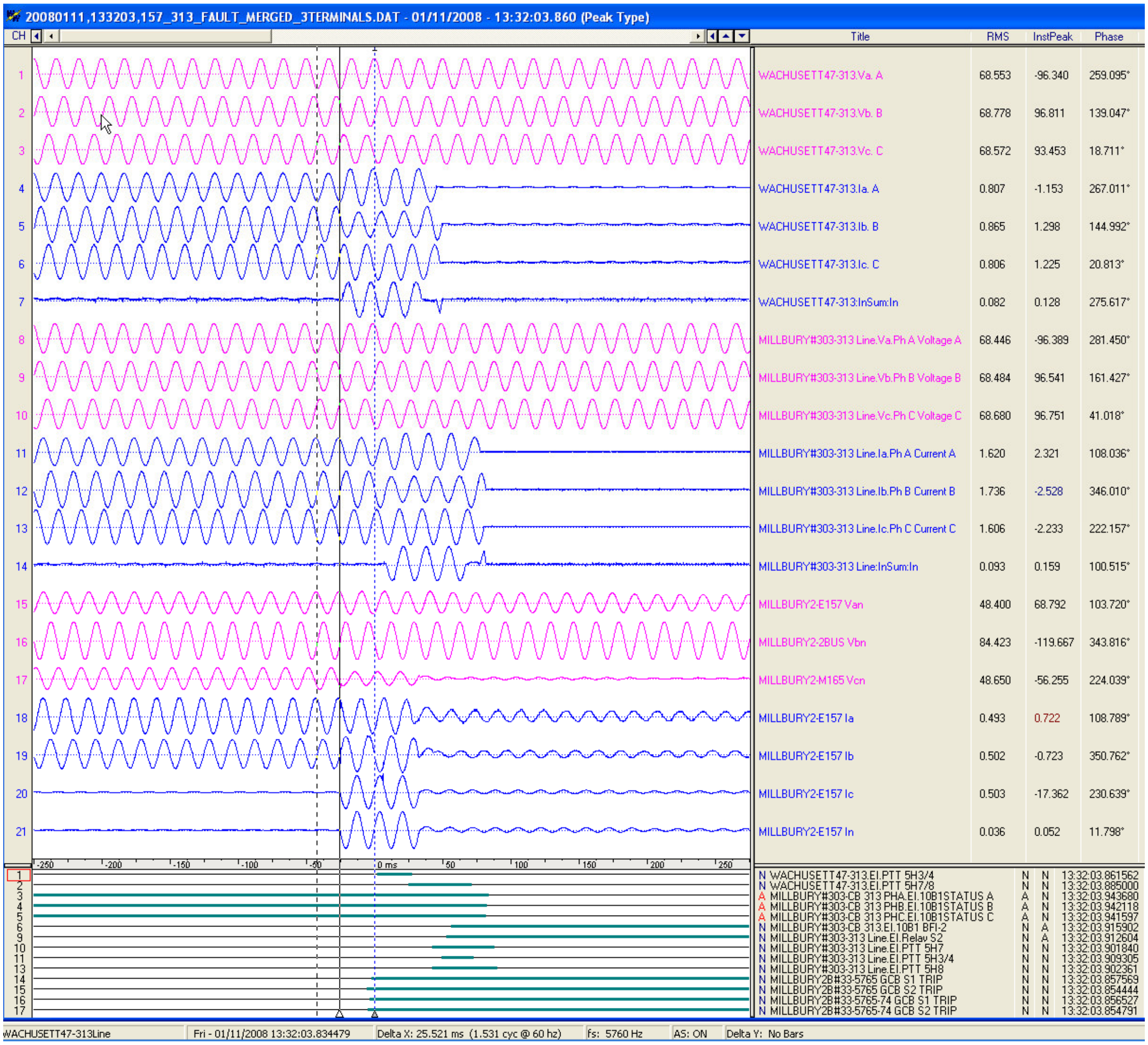

Figure 3. E157 and 313 Line DFR Waveforms at Millbury Substations and Wachusett 47 at 13:32:03

NOTE [1]: The waveforms in Figure 3 and 4 are not to scale. The phase and neutral currents have been enhanced for discussion of the timing discrepancies.

NOTE [2]: Millbury #303 313 Line PTT5H7 and PTT5H8 = 313 Line POTT SEND
Millbury #303 313 Line PTT5H3/4 = 313 Line POTT RECEIVE
Wachusett 47 313 PTT5H3/4 = 313 Line POTT SEND
Wachusett 47 313 PTT5H7/8 = 313 Line POTT RECEIVE

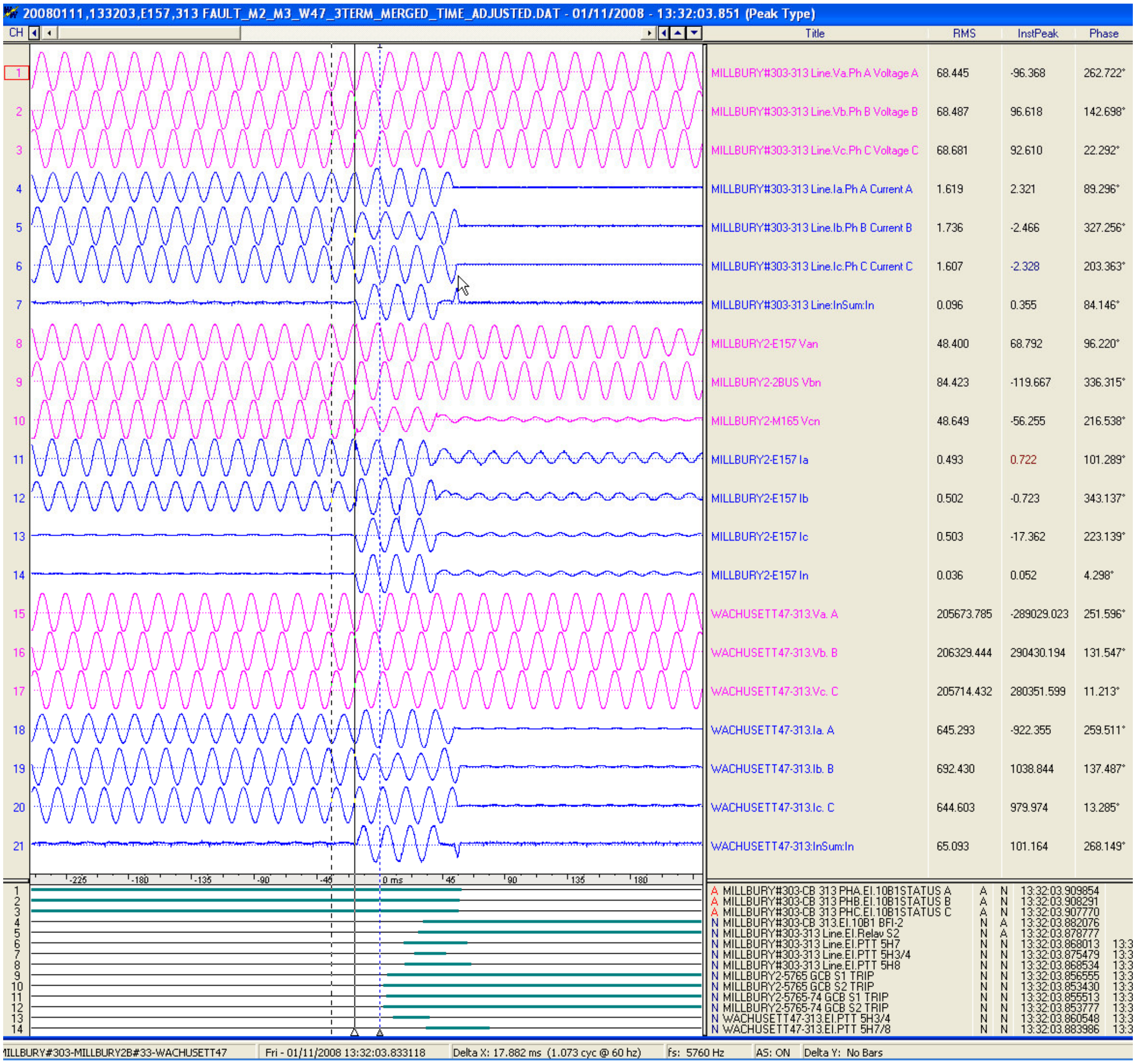

Figure 4. Time Adjusted 313 Line DFR Waveforms from Millbury 3 and E157 and 313 Line at Millbury Substation and Wachusett 47 at 13:32:03

NOTE: Millbury #303 313 Line PTT5H7 and PTT5H8 = 313 Line POTT SEND
Millbury #303 313 Line PTT5H3/4 = 313 Line POTT RECEIVE
Wachusett 47 313 PTT5H3/4 = 313 Line POTT SEND
Wachusett 47 313 PTT5H7/8 = 313 Line POTT RECEIVE

The 313 Line was not faulted, therefore why did the Millbury 3 terminal trip when it should not have? Also, why was there no operation of the 313 Line circuit breakers at Wachusett 47? In order to quantitatively analyze the fault, a simulation was done using a short circuit program. The simulation results concluded that it was a non-bolted fault with a C-phase-to-ground resistance involved (approximately 5 to 7 ohms, see Figure 1). As shown in the 313 relay fault records at Millbury and Wachusett (Table 2 and 3), due to the mutual coupling effect, the ground overcurrent element of the 313 line relays sensed sufficient zero-sequence fault current (3I0) to pickup level, flowing from Millbury to Wachusett. As a result, the instantaneous directional PODG element (67G2) of the 313 line relay at

Millbury operated and sent a permissive input signal (PT) to Wachusett. However, in the meantime, the fault records also indicated that a PT signal was received at Millbury (Figure 4). Upon receiving the PT signal, the permissive tripping condition was met and, consequently, the 313 terminal at Millbury was allowed to operate by the POTT scheme.

Table 1. Prefault and Fault Records of the 313 Line Relay at Millbury

Event: AG T   Location: 172.36   Time Source: OTHER
Event Number: 16838   Shot 1P: 0   Shot 3P: 0   Freq: 60.00   Group: 1
Targets: COMM KEY POTT PHASE A GROUND 50
Breaker 1: CLOSED   Trip Time: 13:32:03.880
Breaker 2: CLOSED   Trip Time: 13:32:03.880

PreFault:	**IA**	**IB**	**IC**	**IG**	**3I2**	**VA**	**VB**	**VC**	**V1mem**
MAG(A/kV)	650	695	645	20	106	205.519	206.594	205.642	205.971
ANG(DEG)	-173.7	64.4	-59.6	-178.8	-51.9	0.0	-120.1	119.4	-0.1
Fault:									
MAG(A/kV)	855	501	663	**507[1]**	**205[3]**	206.502	206.610	190.748	203.393
ANG(DEG)	-159.3	67.1	-61.0	-124.0	-139.8	-1.0	-119.4	118.6	-0.4

Table 2. Prefault and Fault Records of the 313 Line Relay at Wachusett

Event: ER   Location: $$$$.$$ Time Source: OTHER
Event Number: 13945   Shot 1P: 0   Shot 3P: 0   Freq: 60.00   Group: 1
Targets:
Breaker 1: CLOSED
Breaker 2: CLOSED

PreFault:	**IA**	**IB**	**IC**	**IG**	**3I2**	**VA**	**VB**	**VC**	**V1mem**
MAG(A/kV)	652	698	648	19	107	205.591	206.226	205.642	205.822
ANG(DEG)	7.1	-114.9	121.1	9.5	129.0	0.0	-120.1	119.6	-0.1
Fault:									
MAG(A/kV)	861	505	665	**507[1]**	**200[3]**	205.210	204.847	192.105	203.154
ANG(DEG)	20.8	-111.3	119.6	54.8	39.5	0.0	-119.9	118.6	-0.2

NOTE [1] The zero-sequence fault current, IG, is higher than the pickup of the 313 PODG element, 67G2, at Millbury and Wachusett, which is set at 400 primary-amperes.

NOTE [2] The positive-sequence fault current sensed by 313 line relay at Wachusett, i.e. the sum of the vectors of Ia, Ib and Ic is equal to 669 amperes @ 11^0

NOTE [3] The negative-sequence current sensed by 313 line relay at Millbury is slightly higher than the one at Wachusett.

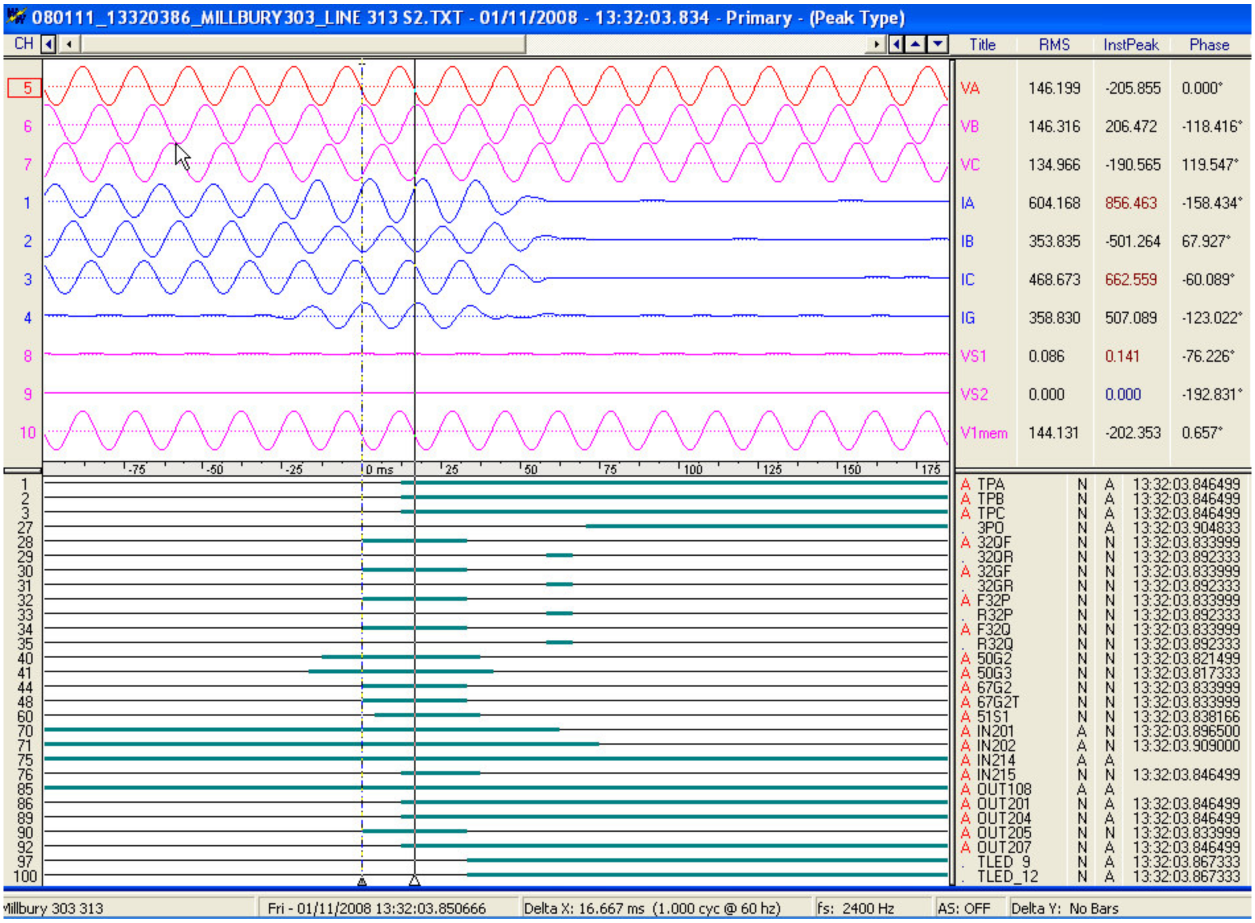

Figure 5. 313 Line POTT Scheme Relay Fault Record at Millbury Substation at 13:32:03

NOTE: IN215 = POTT RECEIVE
OUT205 = KEY POTT

The 313 POTT scheme was set utilizing the relay Echo Logic, with Current Reversal Blocking control, to "echo" the received Permissive Trip (PT) signal to the initiating terminal. As per the manufacturer design, the echo with current reversal logic functions if a reverse fault has not been detected by the reverse-looking elements (phase and ground Zone 3, Z3P and Z3G, and ground overcurrent, 67G3, for this application) before a received PT signal is echoed back. To avoid zero-sequence mutual coupling effect, negative-sequence polarizing is used for directional control on the ground elements used for this application. The following diagrams (Figure 7 & 8) illustrate how the echo with current reversal and the negative-sequence directional control logic works.

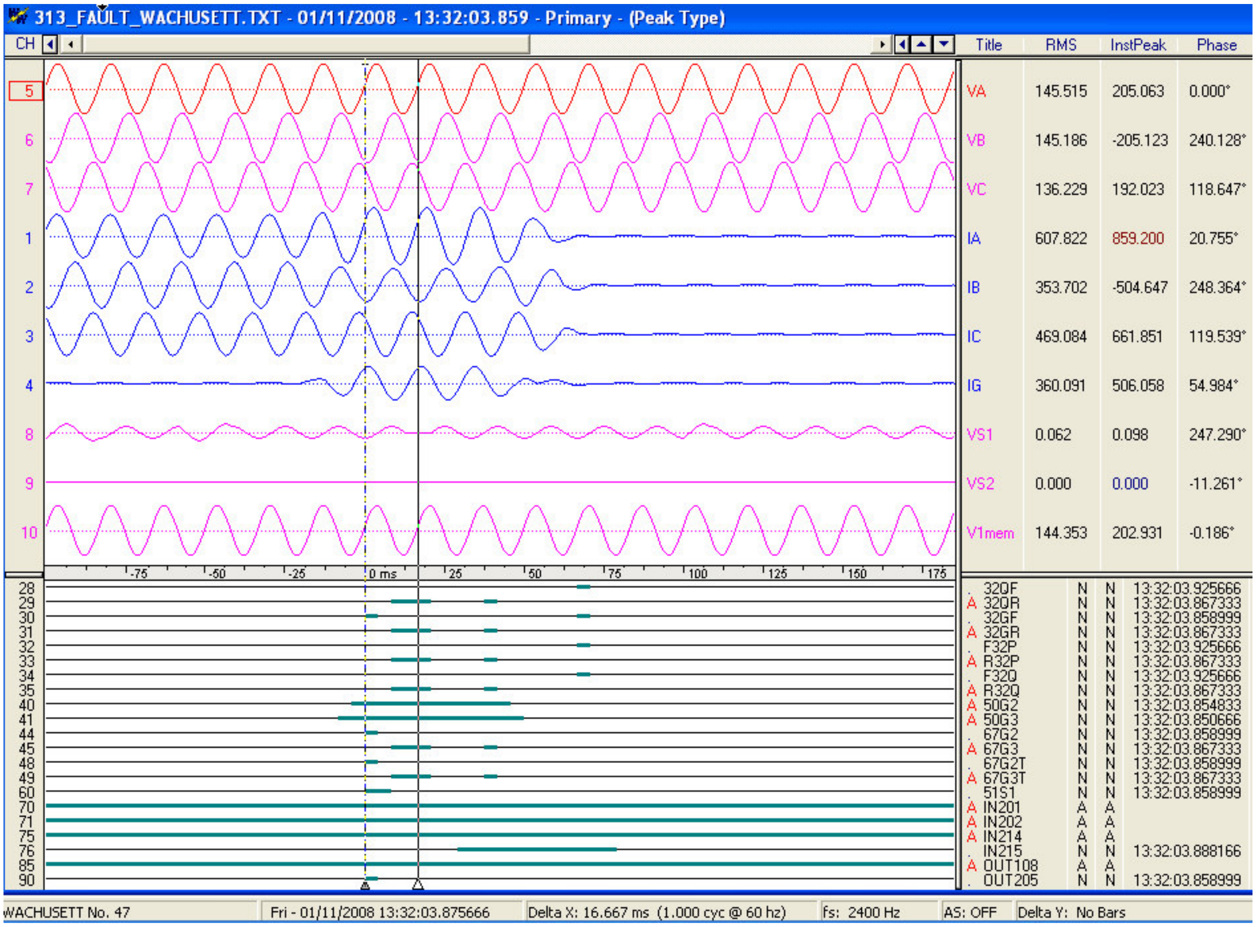

Figure 6. 313 Line 313 POTT Scheme Relay Fault Record at Wachusett Substation at 13:32:03

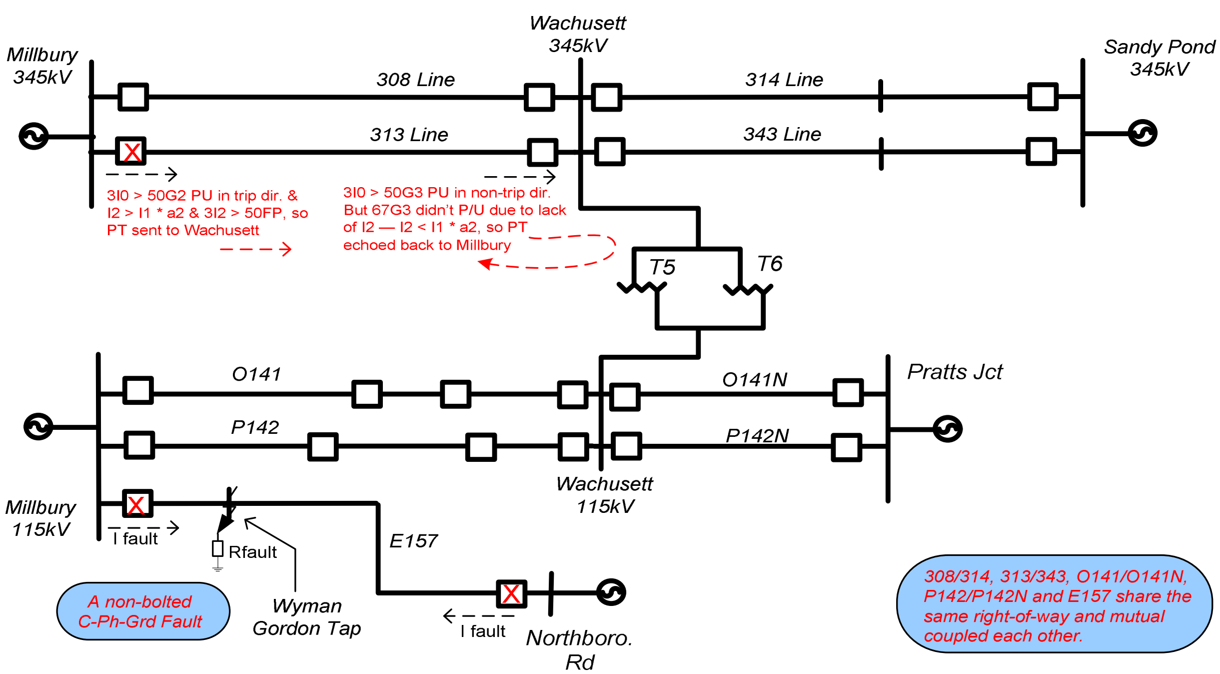

Figure 7. E157 Fault with Response of 313 Echo Logic at Wachusett

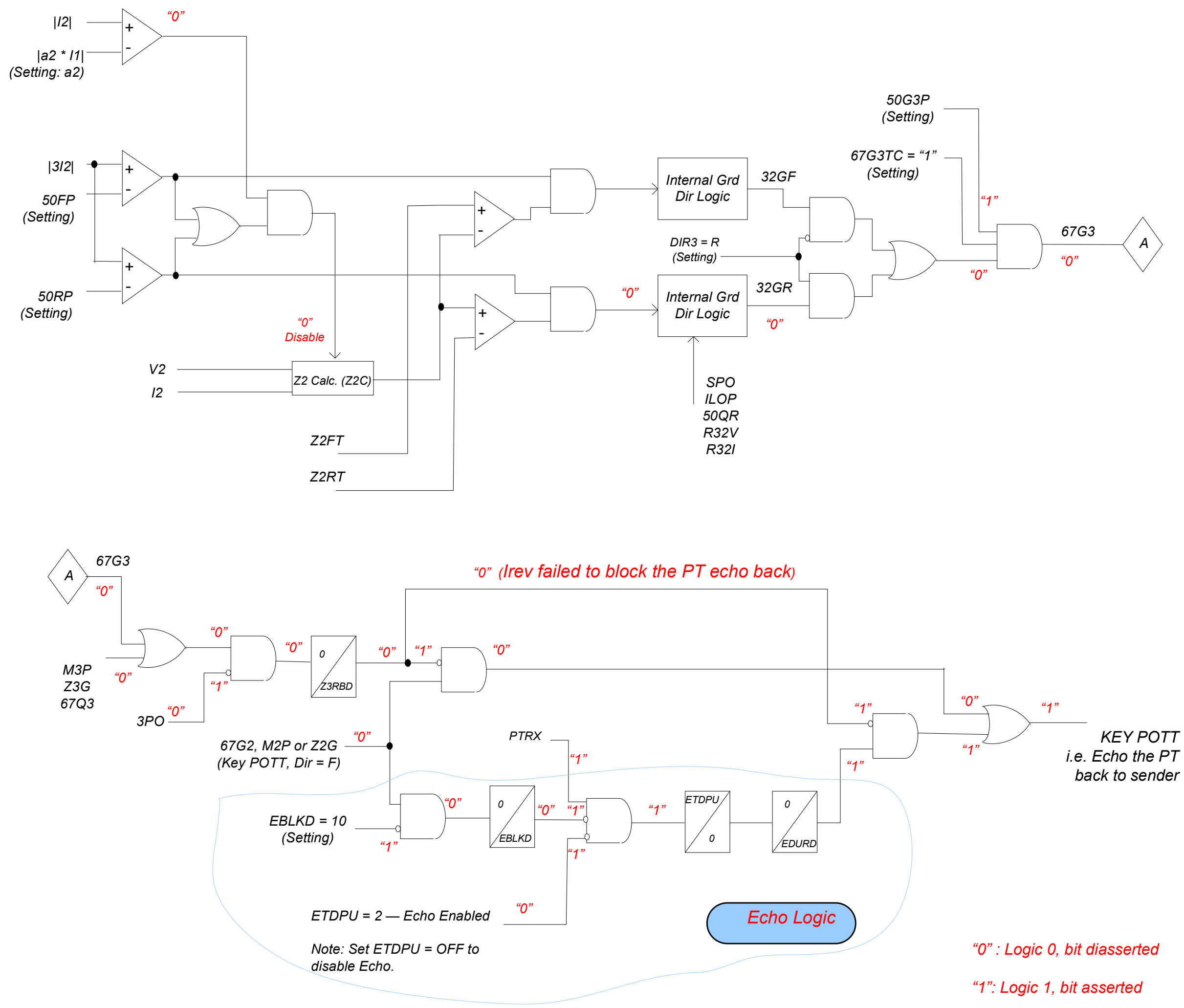

Figure 8. Echo with Current Reversal and Negative-Sequence Directional Element Logic

Comparing the relay fault records for the 313 POTT relay at Millbury 3 (Figure 5) and at Wachusett 47 (Figure 6) and the associated relay settings it was noticed that, at the trigger point, the magnitude of the reverse-looking ground overcurrent element (67G3) at Wachusett 47 was higher than the pre-set pickup level and so the overcurrent element (50G3) of the 67G3 picked up, while the negative-sequence polarized reverse-looking directional element (32GR) did not assert solidly but was right on the edge of operating, in other words, it was toggling between a logic ONE and logic ZERO. As compared with the 32GR, the logic status of the 63G3 was toggled also. As a result, the current reversal element, 67G3, failed to block the received Permissive Trip signal at Wachusett 47 and it echoed back to Millbury 3 (see Figure 7 & 8 for detailed logic). At this point, it was determined that the single-ended POTT operation at Millbury was due to the failure of the negative-sequence polarizing for directional control to assert at Wachusett. The investigation team now focused on determining why the negative-sequence elements associated with the directional control failed to assert.

Following a review of the relay echo and directional control logic shown in Figure 8, at Wachusett, it was determined the following elements could prevent the negative-sequence polarized reverse-looking directional element (32GR) from operating if not set properly.

- Reverse Direction Negative-Sequence Current Detector, 50RP (3I2) – Set the pickup threshold at 0.25/200 amperes (i.e. set at the minimum. tap), or
- Positive-Sequence Restraint Factor, I2/I1, a2 – Set at 0.1 (a typical setting), or
- Zero-Sequence Restraint Factor, I2/I0, k2 – Set at 0.2 (a typical setting)

Based on the records captured by the 313 relay at Wachusett (Table 2), the relay sensed 200 amperes and 669 amperes for 3I2 and I1, respectively, from which the following facts were discovered:

1. The 3I2 detected by the 50RP is the same as the setting of the 50RP, i.e. it is on the edge of assert or de-assert, even though it has been set at the minimum tap to provide maximum sensitivity. Therefore, it is a possible root cause factor in preventing the 32GR element from picking up.
2. Per the manufacturer definition, a2 = I2/I1 = (200/3) / 669 = 0.0997, which is 0.003% smaller than the setting of the a2 element, therefore, it was determined to be a root cause factor in preventing the 32GR and the 67G3 elements from picking up. Consequently, the current reversal element, 67G3, failed to pickup resulting in the scheme failure to block the received PT signal inhibiting the signal from being echoed to the remote end.

The above discovery quantitatively proved that the root cause of the single-end POTT operation at Millbury was due to a lack of negative-sequence current, although only 0.03% lower than the pre-set threshold, for the directional control of the current reversal blocking during the E157 fault at Wachusett.

Lesson's Learned and Conclusions

The analysis team did not immediately recognize the timing discrepancy at the Millbury 3 terminal. An error of 33 milliseconds is significant and impacts the investigation. Not realizing the error could have resulted in an incorrect determination of the mis-operations cause.

The E157 and 313 lines share a common right-of-way with several other lines; therefore there is a significant mutual coupling effect in this area. In order to improve the security of the POTT scheme, and, prevent any parallel line fault from causing an operation on the Permissive Overreaching Transfer Trip (POTT) scheme for external faults, the Echo logic application for the 313 Line was disabled. A review of other lines in the area resulted in the disabling of the ECHO logic in POTT schemes on an additional seven transmission lines.

As a result of the investigation a recommendation to re-evaluate the use of the Echo applications in POTT schemes was made. The determination was that there are cases where the Echo feature could provide needed protection system dependability. However, the use of Echo logic in POTT schemes should be evaluated carefully for each transmission line application as an improper application affects protection system security.

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Jeffrey Pond has been an employee of National Grid for 28 years. 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 recording 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 member of IEEE and is active in several working groups of the Power System Relaying Committee.

References:

1. Schweitzer SEL-421 & SEL-321 Instruction Manuals

2. "Applying the SEL-321 Relay to Permissive Overreaching Transfer Trip (POTT) Schemes", Armando Guzman, Jeff Roberts, Karl Zimmerman, SEL Application Guide – AG95-29.