

Analysis of Simultaneous Faults Using Short Circuit Simulations And Fault Records

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Introduction:

Simultaneous or multi-circuit faults when they occur can be a challenging task to analyze. Prior to 1990 it was very difficult to simulate a simultaneous fault by classical short circuit programs or by hand calculations. Advances in short circuit modeling software allows for the modeling of simultaneous faults. In addition, fault records captured by disturbance monitoring equipment and protective relays provide valuable insight as to the nature of the fault. National Grid has benefited by combining the use of short circuit simulation software and fault records for reliably determining the actual scenarios resulting from these simultaneous or multi-circuits faults. This paper presents two case studies demonstrating the benefits obtained by applying real data from the fault records and the use of simulation tools.

Case One:

On August 14th, 2005, the National Grid System Control Center reported that at 16:01:30 a lightning stroke caused a fault on the 115kV O-141S line near the company's Millbury #302 substation. The substation and faulted line configuration are shown in Figure 1. The circuit breakers O141 and 29-41 at Millbury #302 and O141S at Nashua St tripped correctly by the line protection relays. As per the report, at the time of the O-141S operation, the 115kV P-142S line, one of the parallel lines with the faulted O-141S line, tripped by their line protection relays at Millbury #302 and Rolfe Avenue substations for the O-141S fault. Targets reported for these two operations are as follows:

Millbury #302: O-141S Directional Distance Zone 1, A- B- and C-Phase (DDZ1)
O-141S Directional Ground Overcurrent (DG)

Nashua Street: O-141S Directional Distance Zone 2, B-Phase and Ground (DDZ2)

Millbury #302: P-142S Directional Distance Ground Zone 1 (DDGZ1)

Rolfe Avenue: Targets were not reported. (Note: It is a municipal owned substation.)

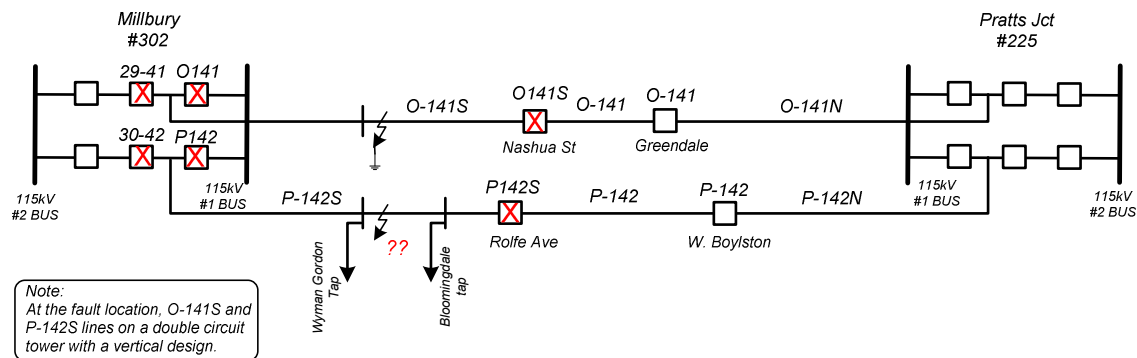


Figure 1. One Line Diagram for O-141 & P-142 Lines

Why did the P-142S line relays respond to the O-141S fault? Was it a single circuit fault only? First, the investigation team verified that the both lines share double-circuit towers with a vertical design between Millbury #302 and Rolfe Avenue, where the P-142S line is more highly insulated than the O-141S line. The conductor phasing arrangements, top to bottom, are B-C-A on the O-141S and A-B-C on the P-142S. Knowing the construction of these lines, it was believed that it would have had to have been a high current stroke to trip both lines. Next, the sequence-of-event and digital fault recorder (DFR) records captured at Millbury #302 were collected, which indicated that the fault occurred on both O-141S and P-

142S lines at 3.06 miles from Millbury #302. Based on the records, the fault involved A-phase-, B-phase- and C-phase-to-ground on the O-141S line and B-phase-to-ground on the P-142S line with fault impedance (Figure 2). It was then further noticed that:

1. The B-phase fault current flowed through the O-141S and P-142S from Millbury #302 were almost in phase, which implies that it was indeed a simultaneous fault. At the cursor (or trigger) point of Figure 2, $I_{b-O-141S}$ was 6.29 @ 151.3⁰ and $I_{b-P-142S}$ was 8.88 @ 153.9⁰ in secondary amperes.
2. The B-phase and the ground (the zero-sequence current, 3I0) fault current flowed on P-142S from Millbury #302 were in phase, which implies that the fault on the P-142S was B-phase-to-ground. At the cursor (or trigger) point of Figure 2, $I_{b-P-142S}$ was 8.88 @ 153.9⁰ and $3I0_{P-142S}$ was 9.65 @ 152.9⁰ in secondary amperes.

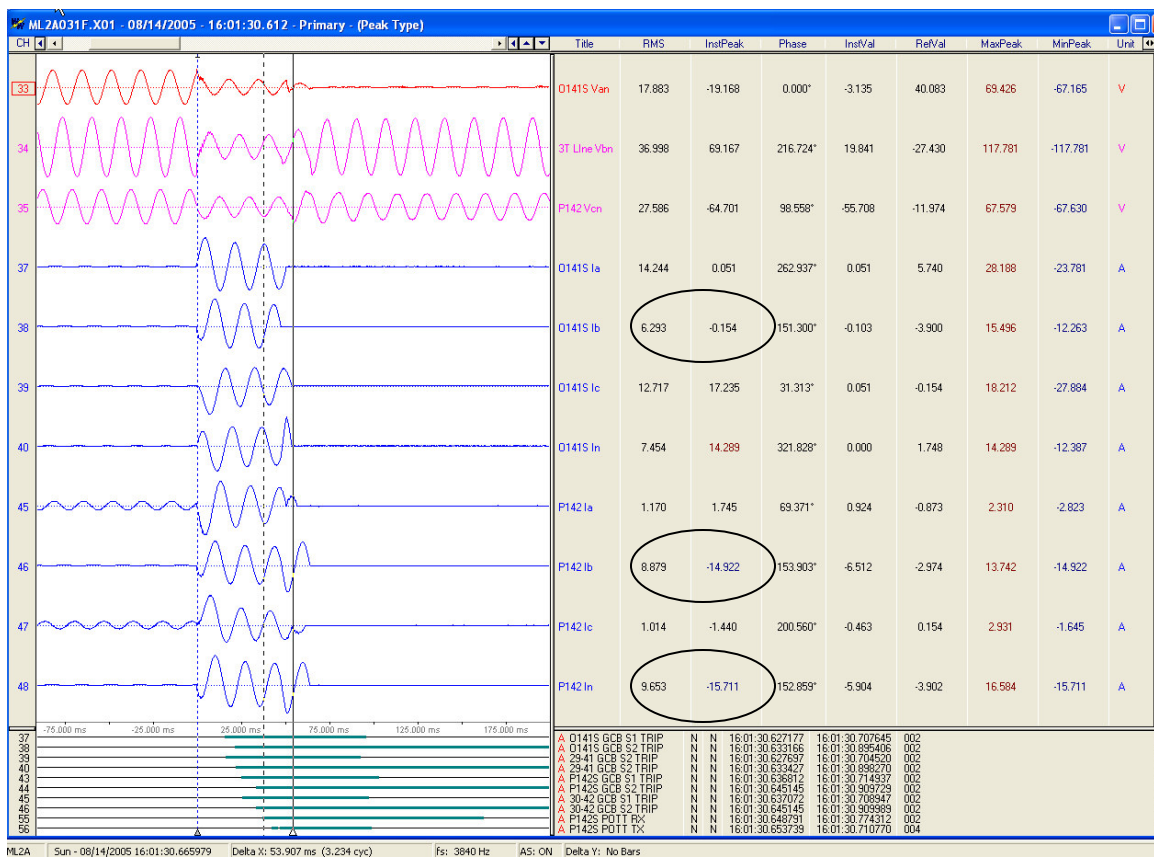


Figure 2. O-141S and P-142S Line DFR Records at Millbury #302

Note: Current is shown in secondary amperes in the record. The CTR for the O-141S and P-142S relays at Millbury #302 is 3000:5.

In order to verify that it was a double-circuit non-bolted fault and all line relays of O-141S and P-142S responded to the event correctly, a simultaneous fault was simulated by using the short circuit program simultaneous fault module. The simulation results proved that:

1. The fault did involve A-, B- and C-phase on the O-141S lines and B-phase-to-ground on the P-142S line simultaneously, and
2. It was a non-bolted fault with phase-to-phase and B-phase-to-ground resistance involved on the O-141S and P-142S line, respectively.

Furthermore, to quantitatively match the fault records captured by the DFR at Millbury 302, more simulations were conducted with a different fault resistance on each phase. Finally, the results concluded that the fault resistance for the O-141S three-phase-to-ground fault was approximately as follows: $R_a = 5.0$ primary-ohms, $R_b = 11.3$ primary-ohms and $R_c = 7.0$ primary-ohms, and the fault resistance for the P-142S B-phase-to-ground fault, R_g , was around 6.5 primary-ohms. (Figure 3 & Table 1)

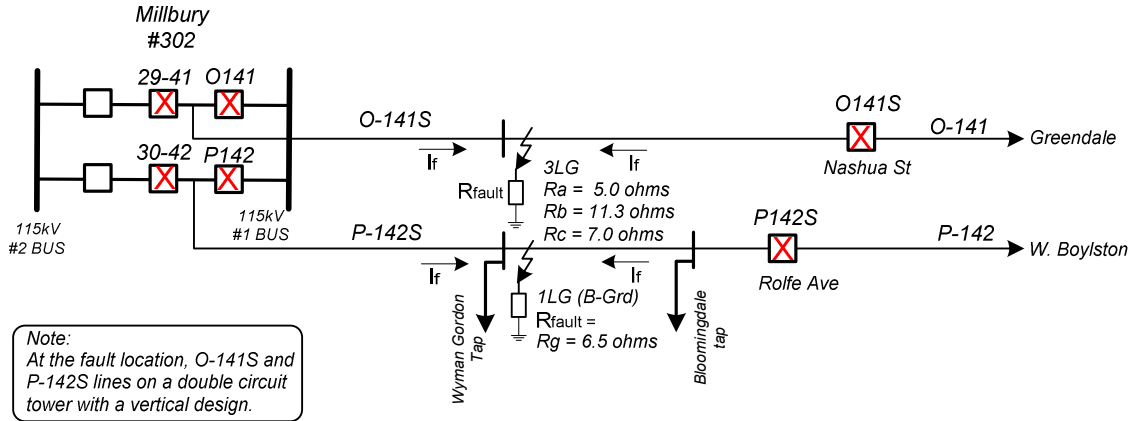


Figure 3. O-141S & P-142S Line Fault

Table 1. Simulation Results of the Simultaneous Fault on O-141S & P-142S Lines
(Output Report of Short Circuit Simulation Program)

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Simultaneous Fault:
Bus Fault on: 50683 WYMAN 1 115. kV 3LG Ra=5 Rb=11.3 Rc=7
Bus Fault on: 50686 WYMAN 2 115. kV 1LG Type=B Rg=6.5
SEE OUTPUT FOR THE FOLLOWING ACTIVE BUS(ES)
1: 50683 WYMAN 1 115 115.kV (O-141S)
2: 50686 WYMAN 2 115 115.kV (P-142S)
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BUS 50683 WYMAN 1 115 115.KV AREA 2 ZONE 1 TIER 0 (PREFault V=1.018@ -0.1 PU)

      + SEQ      - SEQ      0 SEQ      A PHASE      B PHASE      C PHASE
VOLTAGE (KV, L-G) > 52.721@ -30.8  3.047@-136.5  3.306@ 115.8  49.148@ -32.1  50.411@-152.1  58.671@ 91.4
BRANCH CURRENT (A) TO >
0 MILLBURY2 115. 1L 6302.7@ 148.8  1565.3@ 103.3  1288.2@-165.1  8294.7@ 147.5  3537.7@ 27.4  7083.9@ -89.0
50680 ROLFE 1M115 115. 1L 1252.3@ 151.0  204.5@ 113.9  151.7@-171.5  1536.0@ 149.8  924.0@ 29.7  1298.6@ -86.7

CURRENT TO FAULT (A) > 7554.2@ -30.8  1766.7@ -75.5  1439.0@ 14.3  9829.6@ -32.1  4461.1@-152.1  8381.6@ 91.4
THEVENIN IMPEDANCE (OHM) > 3.97359@ 82.0  3.97106@ 81.9  8.67588@ 75.6
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BUS 50686 WYMAN 2 115 115.KV AREA 2 ZONE 629 TIER 0 (PREFault V=1.018@ -0.1 PU)

      + SEQ      - SEQ      0 SEQ      A PHASE      B PHASE      C PHASE
VOLTAGE (KV, L-G) > 54.857@ -19.6  6.196@ -27.4  11.203@ 106.0  55.105@ -10.9  48.806@-157.6  64.040@ 106.6
BRANCH CURRENT (A) TO >
0 MILLBURY2 115. 1L 1405.5@ 139.6  2022.6@ -96.1  1950.0@ 22.0  639.5@ -35.3  5375.8@ 22.1  546.4@ 98.4
0 ROLFE 115. 1L 1012.5@ 146.3  442.4@-103.6  553.2@ 23.9  566.2@ 141.1  2003.4@ 23.5  496.1@ -76.0
650 BLOOMDL 115 115. 1L 88.9@ 142.9  41.3@-104.8  0.0@ 0.0  82.6@ 170.4  129.9@ 20.5  71.5@-124.3
0 WYMAN GORDON 13.8 1T 0.0@ 0.0  0.0@ 0.0  0.0@ 0.0  0.0@ 0.0  0.0@ 0.0  0.0@ 0.0

CURRENT TO FAULT (A) > 2502.9@ -37.6  2502.9@ 82.4  2502.9@-157.6  0.0@ 0.0  7508.6@-157.6  0.0@ 0.0
THEVENIN IMPEDANCE (OHM) > 3.71194@ 82.3  3.70985@ 82.3  7.93466@ 75.2
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Note: Current is shown in primary amperes in the output report.

Case Two:

On May 27, 2007 the System Control Center reported that at 23:33:32 a large oak tree fell on the S197 Line at Brittingham Hill Road near Tower 126 during a thunderstorm. At Bear Swamp 1019 the 197 and T31 circuit breakers (CBs) tripped, and at Deerfield 4 the 3T40 CB tripped (figure 4). At 23:33:33 the 1205W and 1205E CBs opened. At 23:33:37 the 197 CB closed auto and tripped immediately. All breakers were locked out. Targets reported for this disturbance are as follows:

Bear Swamp Switchyard 1019:

- S-197 Directional Distance Fault Detector System 2 (DDFD S2)
- S-197 Instantaneous Overcurrent System 2 (IOC S2) B-Phase
- S-197 Directional Distance Fault Detector System 1 (DDFD S1)
- S-197 Directional Distance Zone 1 System 1 (DD Z1 S1)
- TR1 Line Directional Ground System 1 (DG S1)

Bear Swamp 19:

- TR1 System 1 Transfer Trip

Deerfield 4:

- S-197 Directional Distance Zone 1 (DD Z1 S1)

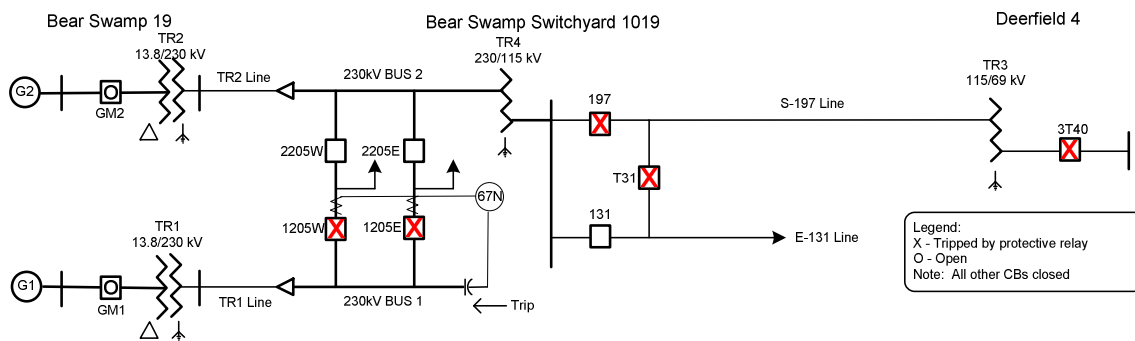


Figure 4. S-197 One-Line Diagram

The S-197 Line fault was confirmed when the tree was found on the line. However, there was no evidence of a fault on the TR1 Line. The TR1 Line operation was a suspected improper operation of the directional ground (67N) protective relay. Was this an improper operation or a separate incident? Prior to the start of the investigation it was confirmed that the power system was operating normally prior to the fault and the generators at Bear Swamp 19, which is a pump storage facility, were off-line. The initial analysis using the one-line diagram in figure 4 agreed with the theory that the TR1 Line protection did mis-operate for the line fault because the faults were behind the protected zone of the TR1 directional ground relay. However, the Control Center report stated that the 1205W and 1205E tripped after the 197 and T31 CBs and before the 197 CB auto-closed suggesting this may be a separate event. The next phase of the analysis was to correlate the reported targets and the fault records retrieved from the DFR at Bear Swamp Switchyard to determine the actual sequence of events for the fault.

Analysis of the fault records determined the initial fault occurred at 23:33:29.610 when the tree fell on the S197 Line causing a B-C-phase fault. The 197 and T31 CBs at Bear Swamp and the 3T40 CB at Deerfield 4 tripped on DD Z1 S1 (figure 5). It was determined that the TR1 Line protection did not operate for the first S-197 fault (figure 6 and 7) or immediately after.

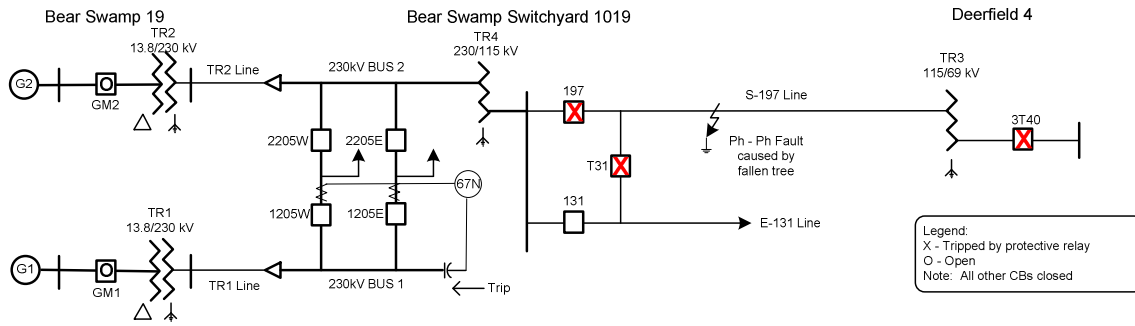


Figure 5. S-197 Line One-Line Diagram – Initial Fault

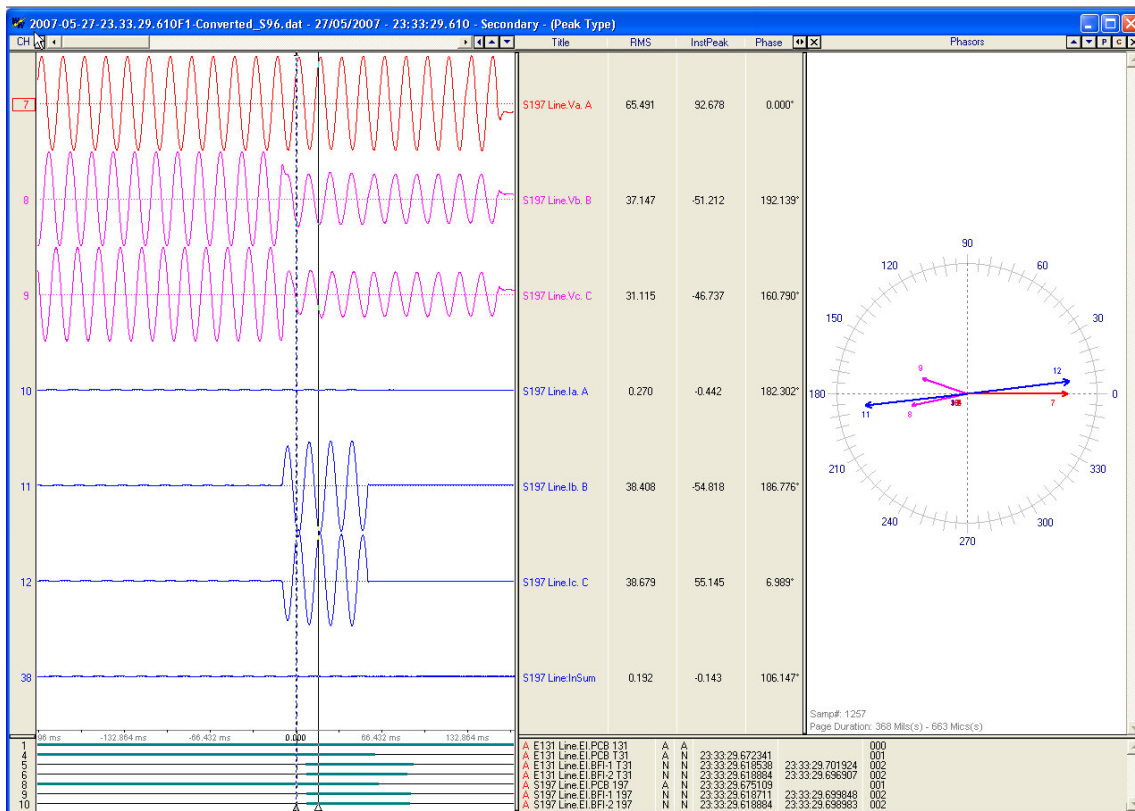


Figure 6. S-197 Line Waveform for Fault at 23:33:29.610

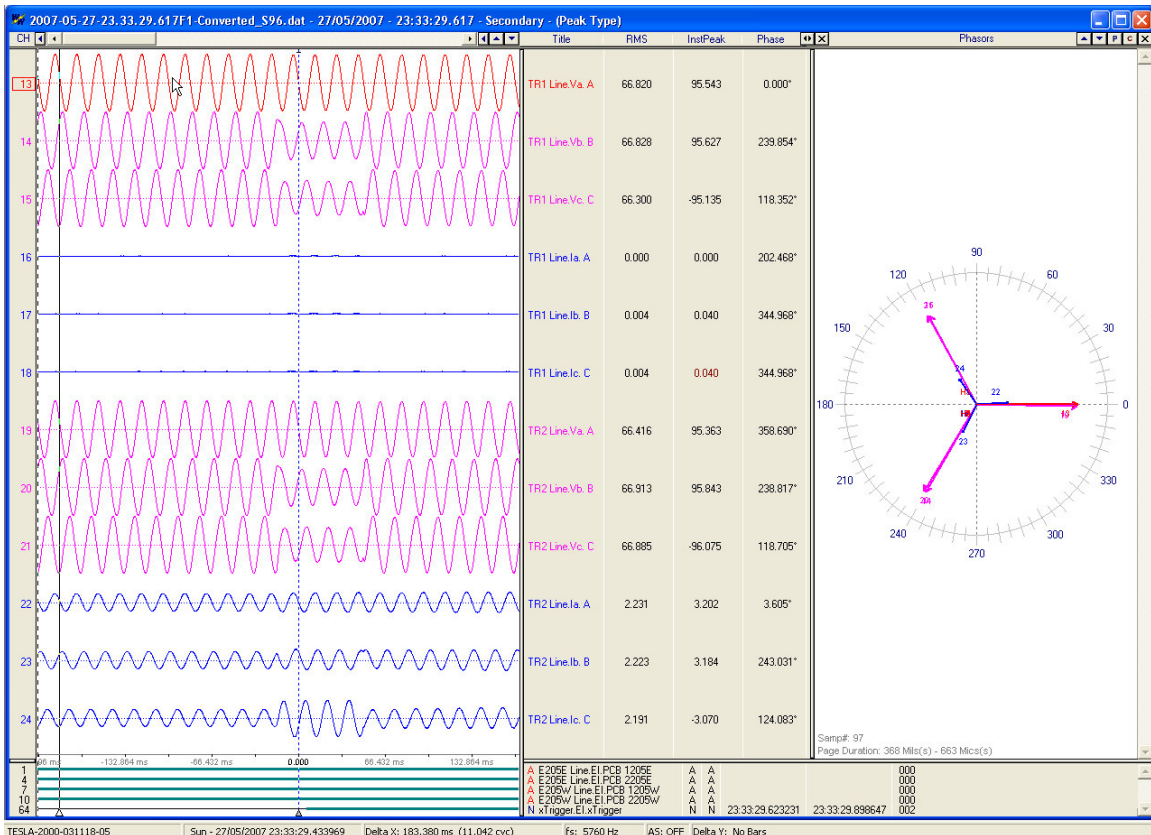


Figure 7. TR1 and TR2 Line Waveforms for Fault at 23:33:29.610

The fault record triggered at 23:33:34.802 shows the 197 CB auto closed, after five seconds, into a B-G fault, caused when a transmission tower was damaged as a result of the fallen tree, and tripped immediately (figure 8 & 9) on S197 IOC B-ph. At the same time the TR1 Line DG relay operated initiating transfer trip to the Bear Swamp Powerhouse, and tripped the 1205E and 1205W CBs (figure 10). The S-197 and TR1 Line CBs were at lockout after the second fault occurred. At this point it was clear the TR1 Line operation was not a separate incident but was the result of the auto-close attempt to re-energize the line. The investigation now focused on what caused the TR1 Line directional ground relay to operate. Further analysis of the fault record in figure 10 determined that the TR1 Line supplied zero-sequence fault current at the time the 197 CB auto-closed. The record shows that the TR1 Line A-, B-, and C-phase currents are additive and are summed in the TR1 Line neutral-current. The results obtained from the analysis now indicate that the TR1 Line directional ground relay operated properly for this fault condition.

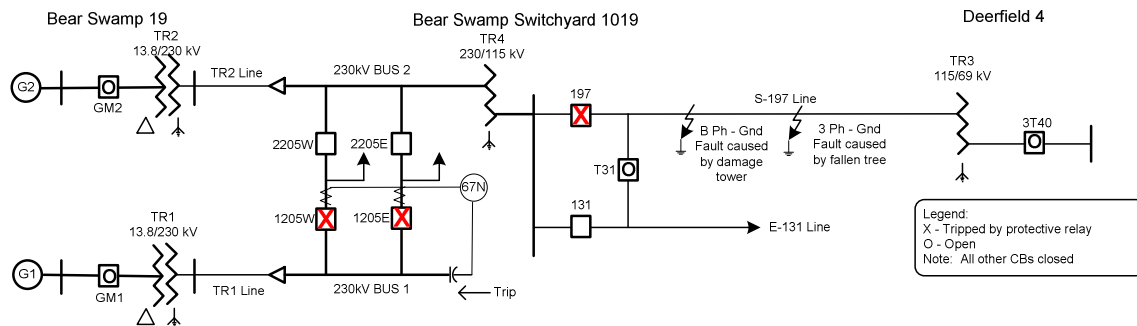


Figure 8. S-197 Line One-Line Diagram – Simultaneous Fault

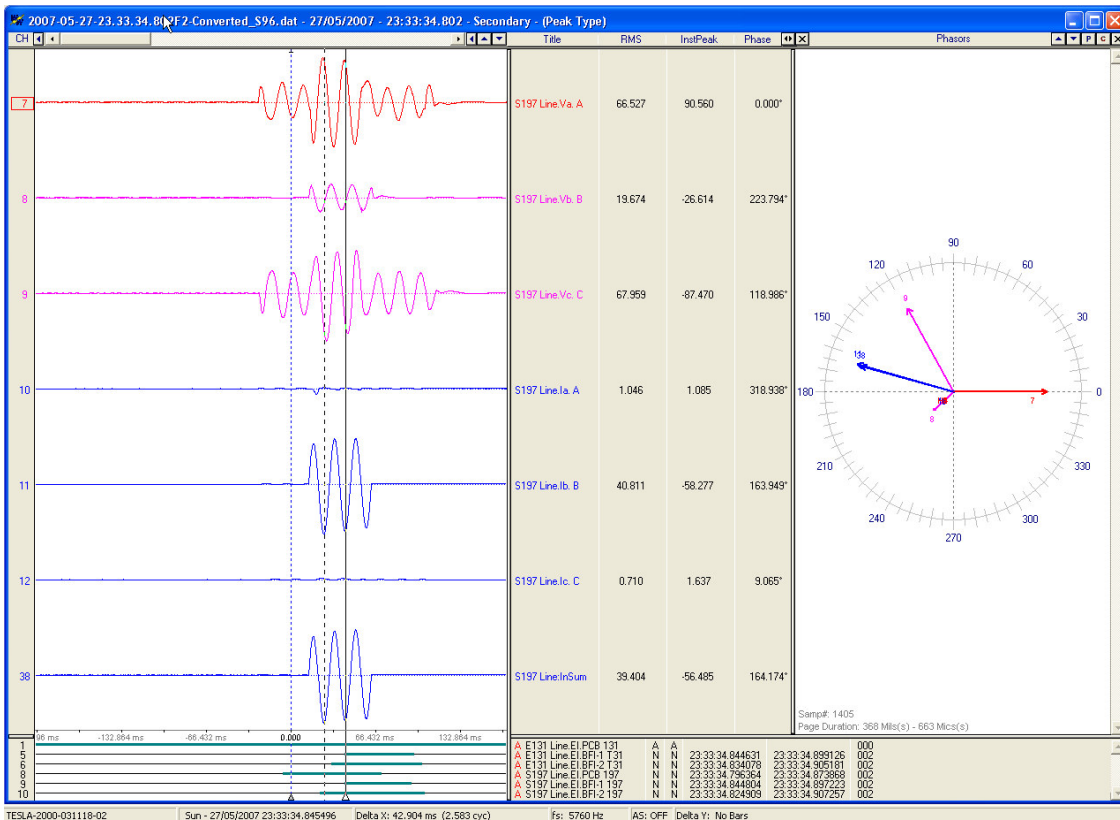


Figure 9. 197 CB Auto-Close into B Ph – Gnd Fault at 23:33:34.802

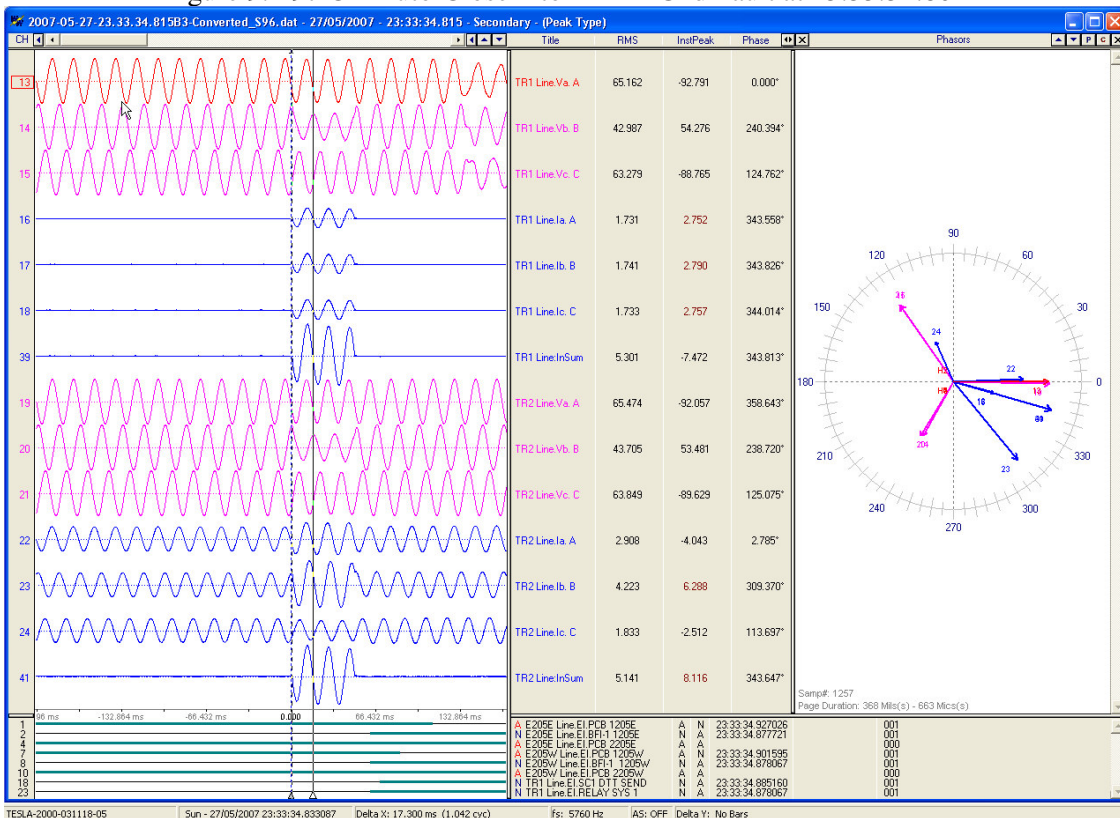


Figure 10. TR1 & TR2 Line Waveforms Second Fault at 23:33:34.802

To confirm the TR1 directional ground relay operated properly for the fault, a short circuit simulation was performed. If the relay operated for the conditions in the fault simulation it would prove the operation was correct, while verifying that National Grid's system model was accurate. The simultaneous fault module would not allow placing two faults on the same line segment, therefore, it was decided that in order to create the simultaneous fault in the short circuit model first, a phase to ground fault was placed on the 115kV Bus at Bear Swamp because tower 126 where the B-phase to ground fault occurred was approximately one mile from the Bear Swamp Switchyard. Second, a three phase to ground fault was placed on the S-197 Line near Bear Swamp (figure 11). The simulation confirmed that the Directional Ground relay, which is a Westinghouse IRQ-9 with negative sequence polarizing, had sufficient polarizing volt-amperes in the forward direction and neutral current to operate. As a final check the TR1 line negative sequence quantities were calculated from the fault records to be 2.88VA, well above the 0.76 VA minimum pickup of the relays directional unit, and the phasors were compared to the IRQ directional unit characteristic. As can be seen in figure 12 the calculated negative-sequence components are similar and match the relay characteristic.

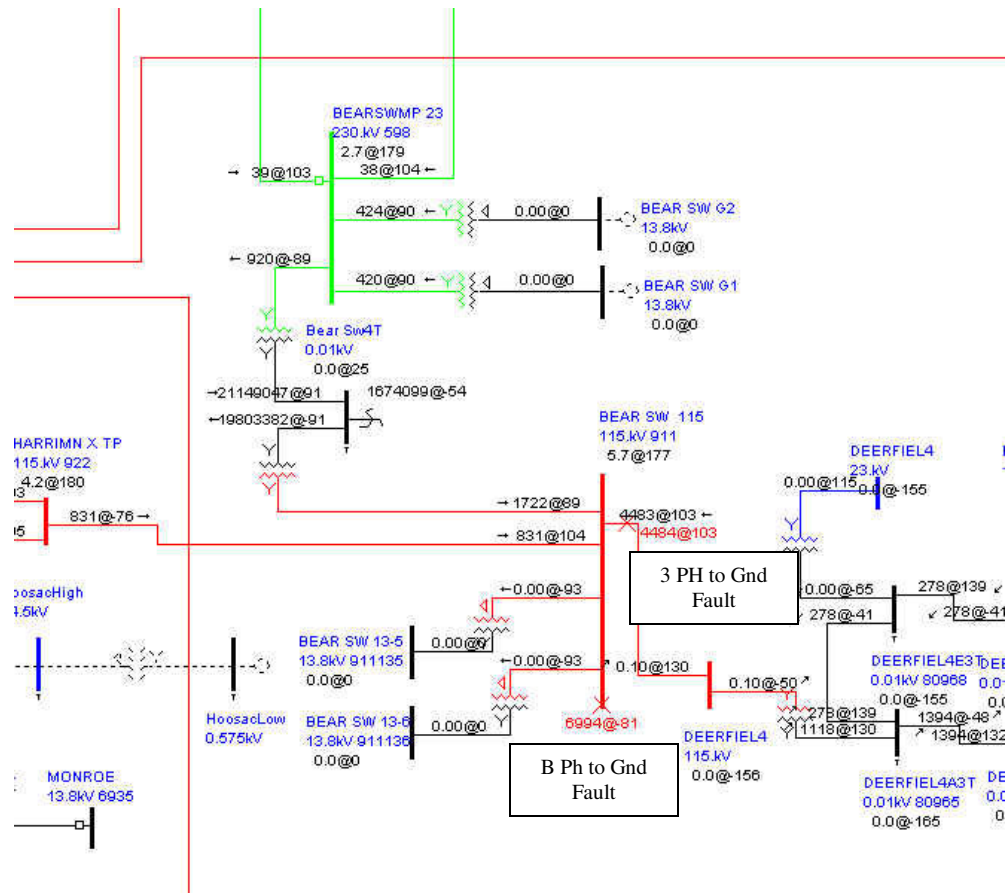


Figure 11. Short Simulation Fault Locations

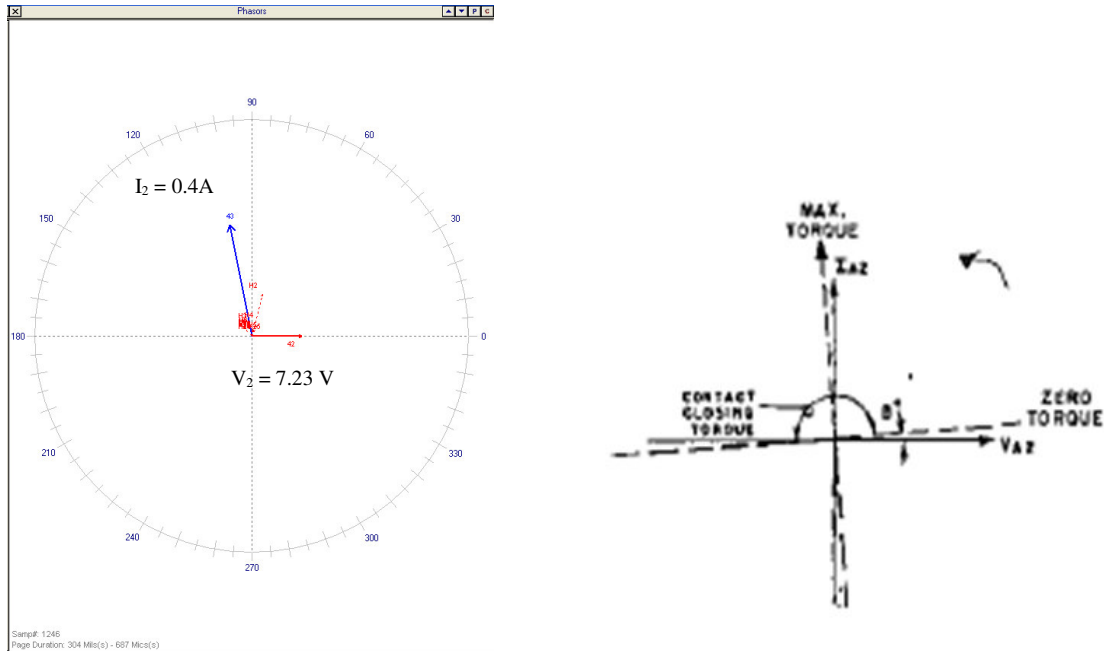


Figure 12. TR1 Negative Sequence Polarizing Comparison with IRQ Characteristic

Based on the analysis it was determined that for the initial fault the S-197 Line directional distance protection operated properly at both Bear Swamp Switchyard and Deerfield 4 for the B- to C-phase fault caused by the falling tree. After the initial phase to phase fault the tree came to rest across all three phases of the S-197 line creating a permanent three-phase to ground fault and causing damage to Tower 126 which is lattice steel construction. As a result of the damage caused by tree falling on the line a permanent B-phase to ground fault was created on the S197 Line at tower 126. When the 197 CB closed auto in five seconds the B-phase to ground fault, caused by the damaged tower, was supplied by the S-197 line at Bear Swamp. The TR1 Line supplied zero-sequence current to the three-phase to ground fault through the Generator 1 GSU at Bear Swamp 19 as was determined from the fault record (figure 10). Based on the analysis the TR1 Line DG relay operation was determined to be a correct operation even though the two faults were behind the relay.

Summary:

National Grid has benefited from the use of digital fault records and short circuit simulation programs for the analysis of power system faults. The digital fault records provide valuable insight as to the nature of the disturbance. The short circuit program features such as the simultaneous fault module have aided the protection engineer in the analysis of faults including simultaneous or multi-circuit faults. Fault records and short circuit programs have provided the engineer with tools that allow them to verify protection system operation and in several cases identify setting changes or control scheme improvements more efficiently and accurately, that make the transmission system more reliable.

Yujie Irene Lu has been employed in National Grid for 18 years. She is a principal engineer in the Department of Protection Engineering, where she performs system analysis for short circuit conditions, design protection systems on a conceptual basis, specify equipment and determine relay settings. In addition, analyzes disturbances on transmission and supply networks. Previously, Irene worked for the Department of Energy of China for 5 years. Irene received a BSEE degree in Power Systems Engineering from Huazhong University of Science & Technology in China, and a MSEE in Electrical Engineering from Virginia Polytechnic Institute in Blacksburg, VA. She is a member of IEEE and a registered professional engineer in MA.

Jeffrey Pond has been an employee of National Grid for 27 years. He is a Lead Technician in 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. Westinghouse Instruction Manual I. L. 41-133.2F, Type IRQ Directional Overcurrent Negative Sequence Relay for Ground Protection
2. "Fault Analysis Using Protective Relay Digital Fault Records From the Big Rivers Electric Corporation 161 kV System", Elmo Price, Bob Warren; 2003 Fault and Disturbance Conference, Atlanta, Georgia, May 2003.