ANALYSIS of a CASCADING EVENT at NATIONAL GRID

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INTRODUCTION

On November 16, 2007 a shield wire failure within National Grid's Sandy Pond substation initiated an event that cascaded, resulting in the failure of a 345/115 kV transformer and the loss of the nearby HVDC Converter Terminal supply. Cascading events are of concern to utilities and the Regional Transmission Organizations (RTO). For the utility, the protection schemes need to work properly to isolate faults quickly, minimizing the impact on transmission system. Isolation of faulted components quickly is necessary in order to maintain system reliability and stability. For the RTO if the failed components are not isolated the impact on power system stability could potentially cause a wide-area event.

This paper provides a detailed review of the event and an analysis of the protection scheme operations based on data collected by disturbance monitoring equipment. The sequence of events will be presented along with a determination of which protection systems operated properly and which, if any, operated improperly. The paper will also describe the impact on the local and regional interconnection and the potential for a major wide area interconnection event.

THE EVENT

On 11/16/2007 the System Control Center reported that at 14:54:38 the I-161 Line shield wire failed and fell across the 1612 circuit breaker (CB) causing a fault tripping the I161 and 1612 CBs. The fault caused Transformer 1 to fail. The 314, 3521, 326, K-137W, L-138W, and 231 CBs tripped and locked out. At the same time the 3512, 337, 343, K-137E, L-138E and, 232 CBs on Bus 2 tripped and locked out. The 1412 and 2137 CBs then tripped. Figure 1 shows the position of the circuit breakers and disconnects at Sandy Pond after all faults were cleared.

Reported targets are as follows:

Sandy Pond 237:
- I-161W System 1 Directional Distance Zone 1, System 1 Directional Distance Fault Detector;
- I-161W, System 2 Directional Distance Zone 1, System 2 Directional Distance Fault Detector;
- TR1 Overall Differential B- & C-phase,
- TR1 Transformer Differential and TR1 Lockout relay;
- TR2 Overall Differential B- & C-phase, and TR2 Lockout relay.

Sandy Pond HVDC:
- Bus 1 Over Voltage;
- Bus 2 Over Voltage

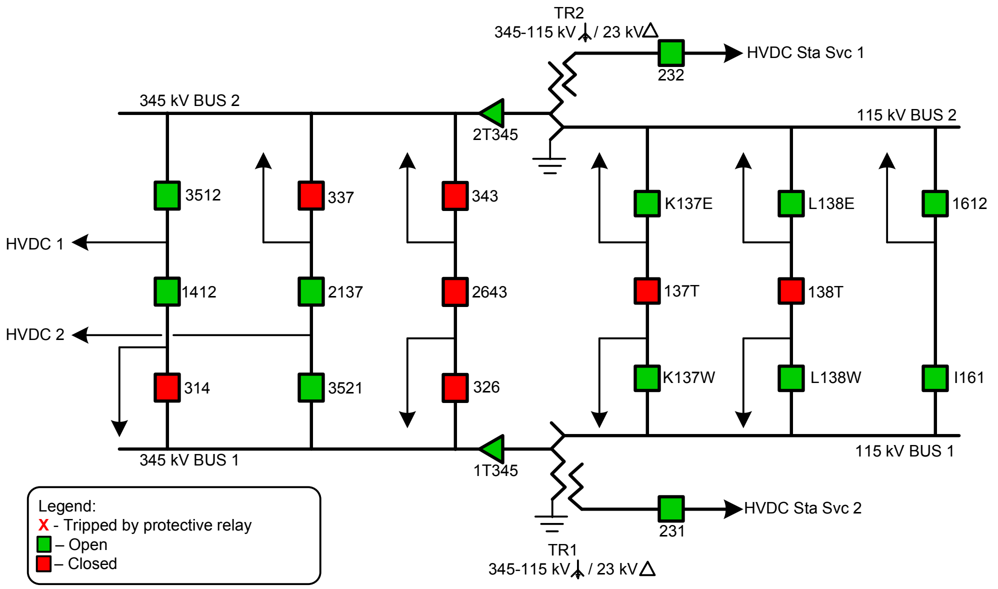


Figure 1 – One-line Station Configuration at End of Cascade Event

EVENT ANALYSIS

The first step in the analysis was to assemble the sequence of events and to match the reported relay targets with the operations that occurred. The disturbance was divided into five separate events with the associated relay targets, based on the time stamps, as can be seen in Table 1.

Table 1 - SEQUENCE OF EVENTS - SANDY POND

EVENT	TIME	SUBSTATION	DEVICE	STATUS	REPORTED TARGETS
1	14:54:38.755	SANDY PD 115	1612 CB	OPEN	I161W S1 DDFD & DD Z1
	14:54:38.755	SANDY PD 115	I161 CB	OPEN	I161W S2 DDFD & DD Z1
2	14:54:44.038	SANDY PD 23	231 CB	OPEN	TR1 OD B & C Phase TR1 TD
	14:54:44.042	SANDY PD 345	326 CB	OPEN	
	14:54:44.046	SANDY PD 345	314 CB	OPEN	
	14:54:44.068	SANDY PD 115	L138W CB	OPEN	
	14:54:44.077	SANDY PD 345	3521 CB	OPEN	
	14:54:44.092	SANDY PD 115	K137W CB	OPEN	
	14:54:45.496	SANDY PD 345	1T345 MOD	OPEN	
3	14:54:46.616	SANDY PD 345	337 CB	OPEN	TR2 OD B & C Phase
	14:54:46.623	SANDY PD 23	232 CB	OPEN	
	14:54:46.631	SANDY PD 345	343 CB	OPEN	
	14:54:46.642	SANDY PD 345	3512 CB	OPEN	
	14:54:46.690	SANDY PD 115	K137E CB	OPEN	
	14:54:46.703	SANDY PD 115	L138E CB	OPEN	
	14:54:47.170	SANDY PD 345	2T345 MOD	OPEN	
4	14:54:54.984	SANDY PD 345	1412 CB	OPEN	BUS 1 OV DTT
	14:54:55.051	SANDY PD 345	2137 CB	OPEN	BUS 2 OV DTT
5	14:55:04.664	SANDY PD 345	326 CB	CLOSE	Auto-Close Live Line - Dead Bus
	14:55:09.902	SANDY PD 345	314 CB	CLOSE	
	14:55:11.784	SANDY PD 345	343 CB	CLOSE	
	14:55:17.081	SANDY PD 345	337 CB	CLOSE	

Once a time-line of the events is established using the SOE records and reported targets, the next step is to analyze the fault records that were captured for the event. Analysis of the fault records provides additional detail which helps to more accurately determine what occurred during the event to evaluate the performance of protective relay systems.

The initial fault was caused when the shield wire broke free of the structure and fell coming in contact with the I-161 Line section of the bus as depicted in the one-line in Figure 2. The fault record captured for this event (Figure 3) shows a C-phase to ground fault exceeding 15,000 Amps that cleared in approximately three cycles when the I161 and 1612 circuit breakers (CB) tripped. The circuit breaker change-of-state in Figure 3 agrees with the sequence-of-events for Event 1 in Table 1. The I161 system one and two Directional Distance Zone 1 targets reported by the System Control Center align with this operation based on the protection zone of the relays, which is identified by the highlighted area shown in Figure 2.

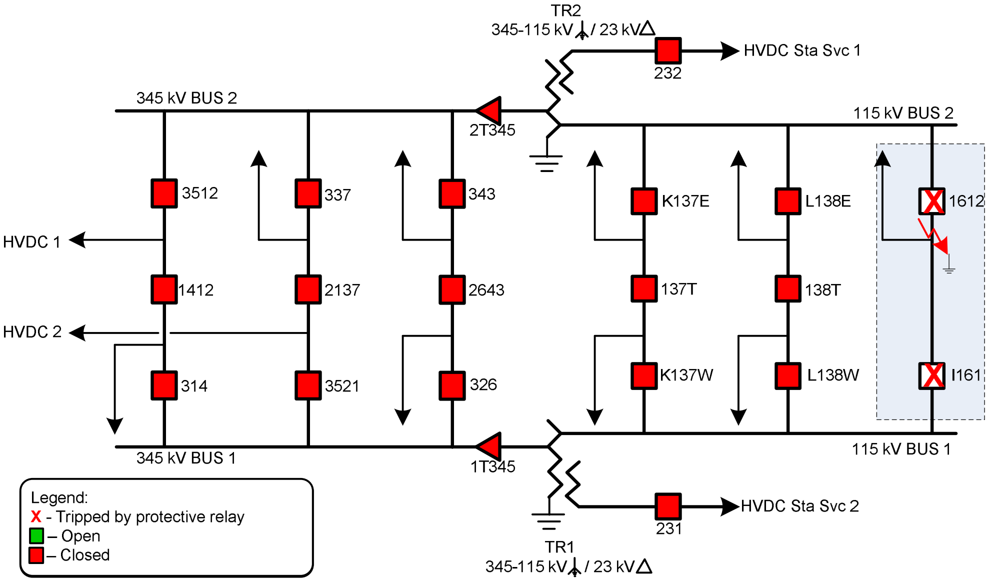
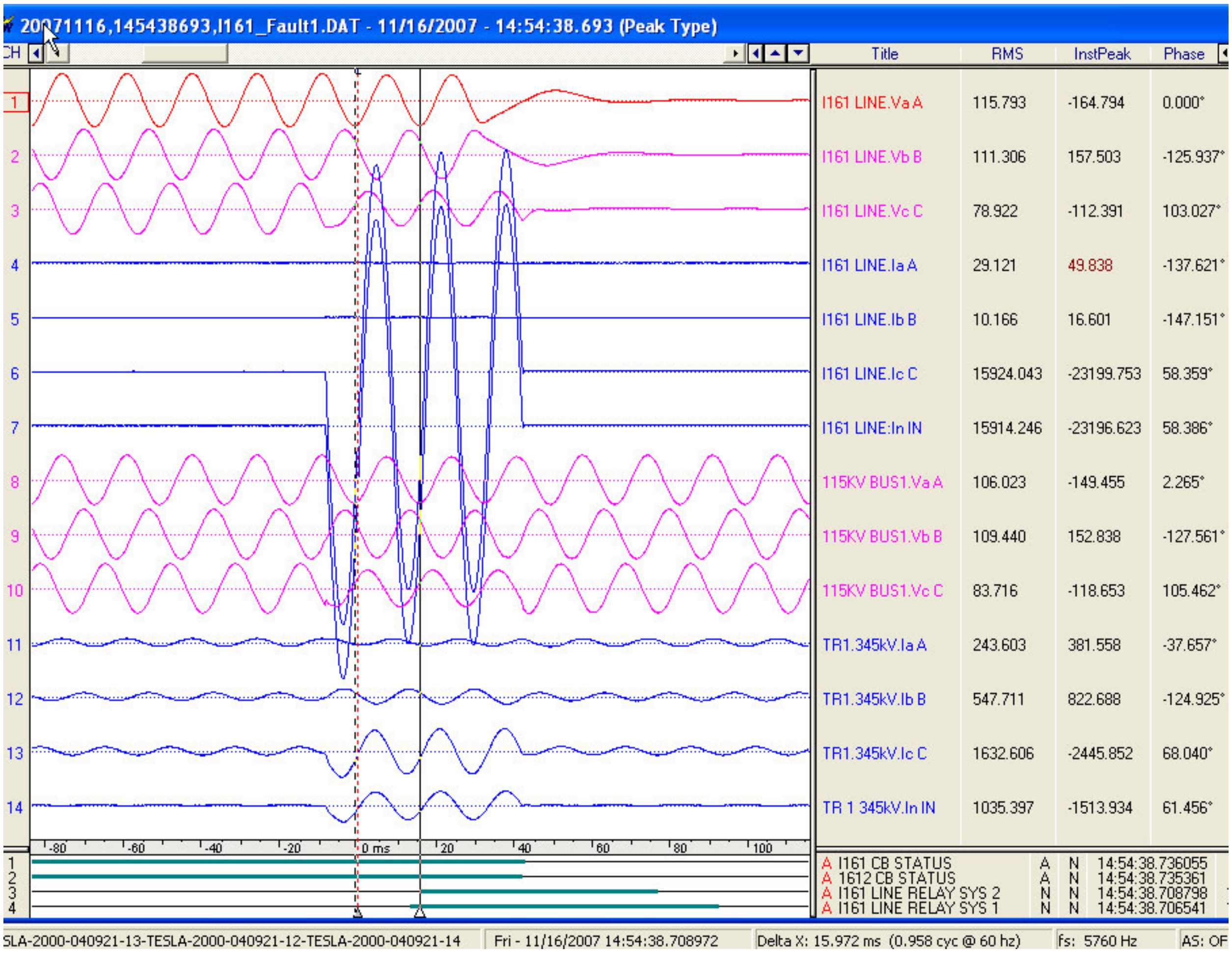


Figure 2 – Initial I161 fault


20071116,145438693,I161_Fault1.DAT - 11/16/2007 - 14:54:38.693 (Peak Type)

CH	Title	RMS	InstPeak	Phase
1	I161 LINE.Va A	115.793	-164.794	0.000°
2	I161 LINE.Vb B	111.306	157.503	-125.937°
3	I161 LINE.Vc C	78.922	-112.391	103.027°
4	I161 LINE.Ia A	29.121	49.838	-137.621°
5	I161 LINE.Ib B	10.166	16.601	-147.151°
6	I161 LINE.Ic C	15924.043	-23199.753	58.359°
7	I161 LINE:In IN	15914.246	-23196.623	58.386°
8	115KV BUS1.Va A	106.023	-149.455	2.265°
9	115KV BUS1.Vb B	109.440	152.838	-127.561°
10	115KV BUS1.Vc C	83.716	-118.653	105.462°
11	TR1.345kV.Ia A	243.603	381.558	-37.657°
12	TR1.345kV.Ib B	547.711	822.688	-124.925°
13	TR1.345kV.Ic C	1632.606	-2445.852	68.040°
14	TR 1 345kV.In IN	1035.397	-1513.934	61.456°

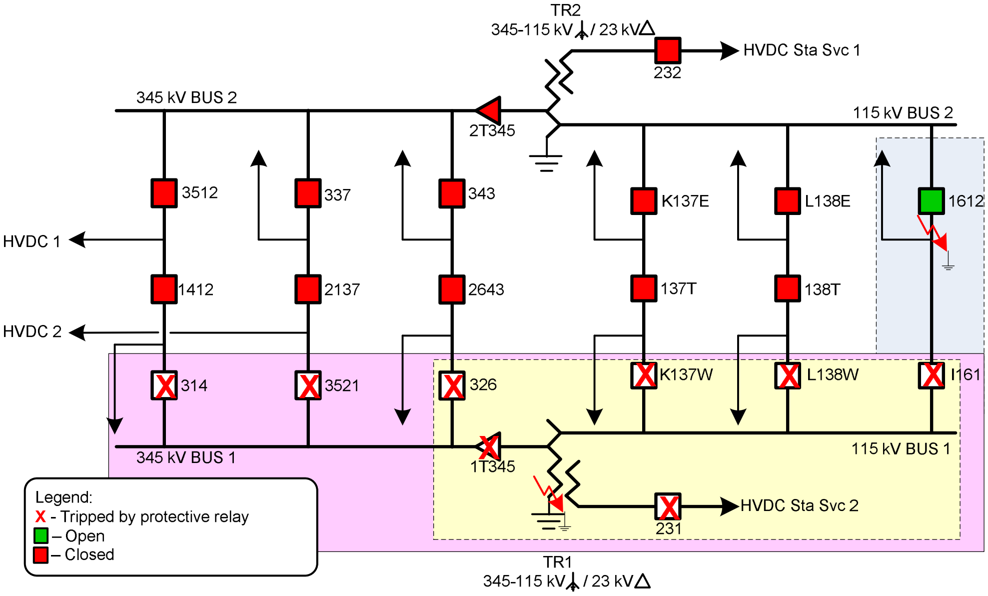
1	A I161 CB STATUS	A	N	14:54:38.736055
2	A 1612 CB STATUS	A	N	14:54:38.735361
3	A I161 LINE RELAY SYS 2	N	N	14:54:38.708798
4	A I161 LINE RELAY SYS 1	N	N	14:54:38.706541

SLA-2000-040921-13-TESLA-2000-040921-12-TESLA-2000-040921-14 | Fri - 11/16/2007 14:54:38.708972 | Delta X: 15.972 ms (0.958 cyc @ 60 hz) | fs: 5760 Hz | AS: OF

Figure 3 – Initial Fault caused by failed shield wire

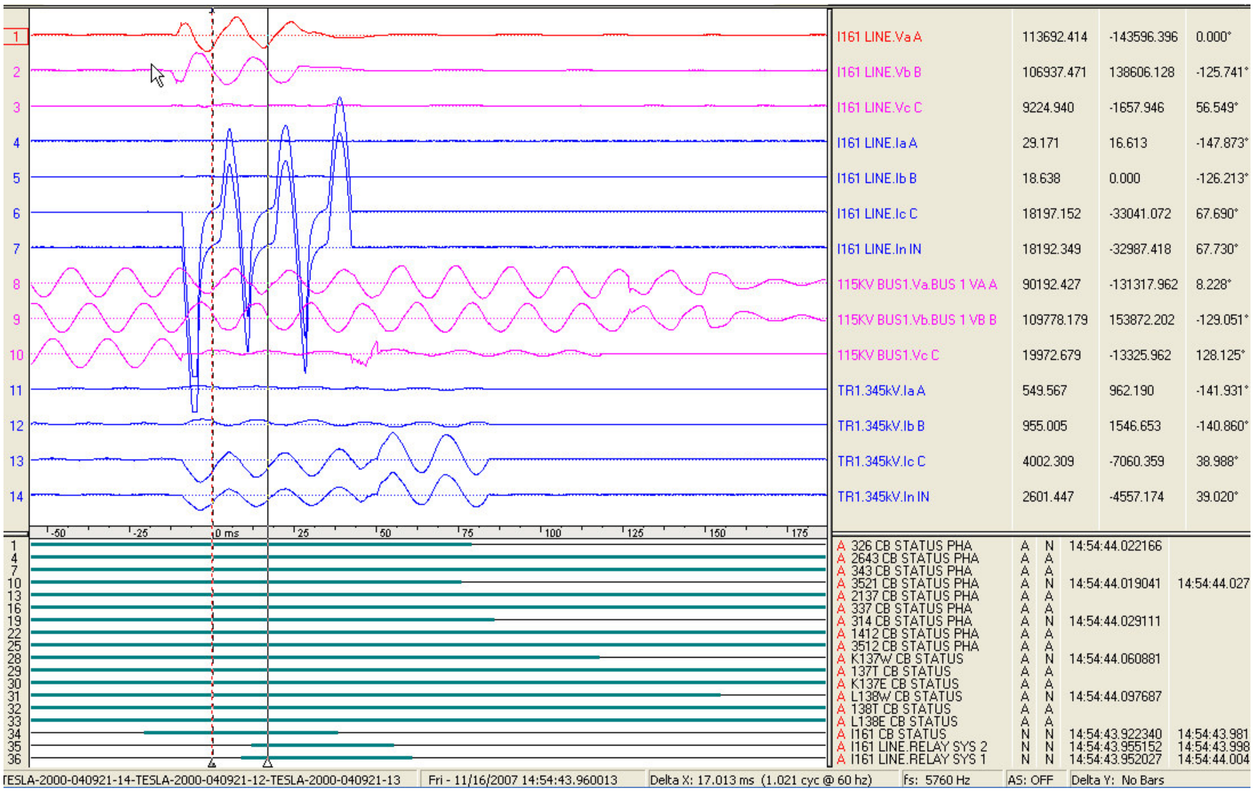
The second event occurs approximately five seconds after the initial fault, as can be seen in Table 1. During this event the TR1 Overall Differential protection and Transformer Differential protection operated tripping the Bus 1 345kV and 115kV circuit breakers to lockout as depicted in Figure 4. The 1T345 motor operated disconnects on the 345kV side of TR1 also tripped. The protection zones of the Overall Differential protection and Transformer Differential protection are highlighted in red and yellow respectively for reference in Figure 4. Review of the fault record (Figure 5) captured for this event shows that the I161 CB closed into a fault caused by the failed shield wire. The fault record shows TR1 supplying fault current for the I161 fault. The I161 circuit breaker trips in approximately three-cycles at which point the C-phase and neutral current supplied by TR1 increases. It is possible that the transformer fails at the point where the I-161 fault clears because of the increase in fault current supplied by the transformer. The transformer fault clears approximately two and one-half -cycles after the I161 CB opens clearing the I161 fault. No targets were assigned for the I161 CB operation in Event 2 of Table 1. It is possible that the trip was initiated by the I-161 Line Directional Distance protection, however, it is more likely that the I161 CB tripped on Instantaneous Over-Current (IOC) protection of which no target was reported. The IOC protection is designed to trip its associated circuit breaker if it is closed into a permanent fault, similar to Switch-on-to-Fault protection today.

A review of the protective relay and control settings identified that for an I-161 line fault the I161 CB will auto-close in five (5) seconds. This five second auto-close matches the time that lapsed between the first and second event. As discussed above it was confirmed in the fault record that the I161 CB attempted to close into a permanent fault caused by the failed shield wire. The sequence-of-events table does not show this auto-close.



Legend:
X - Tripped by protective relay
🟩 – Open
🟥 – Closed

Figure 4 – I161 CB Auto-Close and TR1 Failure



I161 LINE.Va A	113692.414	-143596.396	0.000°
I161 LINE.Vb B	106937.471	138606.128	-125.741°
I161 LINE.Vc C	9224.940	-1657.946	56.549°
I161 LINE.Ia A	29.171	16.613	-147.873°
I161 LINE.Ib B	18.638	0.000	-126.213°
I161 LINE.Ic C	18197.152	-33041.072	67.690°
I161 LINE.In IN	18192.349	-32987.418	67.730°
115KV BUS1.Va.BUS 1 VA A	90192.427	-131317.962	8.228°
115KV BUS1.Vb.BUS 1 VB B	109778.179	153872.202	-129.051°
115KV BUS1.Vc C	19972.679	-13325.962	128.125°
TR1.345kV.Ia A	549.567	962.190	-141.931°
TR1.345kV.Ib B	955.005	1546.653	-140.860°
TR1.345kV.Ic C	4002.309	-7060.359	38.988°
TR1.345kV.In IN	2601.447	-4557.174	39.020°

A 326 CB STATUS PHA	A	N	14:54:44.022166	
A 2643 CB STATUS PHA	A	A		
A 343 CB STATUS PHA	A	A		
A 3521 CB STATUS PHA	A	N	14:54:44.019041	14:54:44.027
A 2137 CB STATUS PHA	A	A		
A 337 CB STATUS PHA	A	A		
A 314 CB STATUS PHA	A	N	14:54:44.029111	
A 1412 CB STATUS PHA	A	A		
A 3512 CB STATUS PHA	A	A		
A K137W CB STATUS	A	N	14:54:44.060881	
A 137T CB STATUS	A	A		
A K137E CB STATUS	A	A		
A L138W CB STATUS	A	N	14:54:44.097687	
A 138T CB STATUS	A	A		
A L138E CB STATUS	A	A		
A I161 CB STATUS	N	N	14:54:43.922340	14:54:43.981
A I161 LINE.RELAY SYS 2	N	N	14:54:43.955152	14:54:43.998
A I161 LINE.RELAY SYS 1	N	N	14:54:43.952027	14:54:44.004

TESLA-2000-040921-14-TESLA-2000-040921-12-TESLA-2000-040921-13 | Fri - 11/16/2007 14:54:43.960013 | Delta X: 17.013 ms (1.021 cyc @ 60 hz) | fs: 5760 Hz | AS: OFF | Delta Y: No Bars

Figure 5 – I161 CB Auto Close and Transformer 1 Failure

There are several factors as to why a remote terminal unit (RTU) may not detect a circuit breaker change-of-state in a sequence-of-events record. The first being when the breaker is closed into a permanent fault the breaker mechanism typically does not fully latch and an auxiliary contact may not completely make during a trip-free operation. The second factor is where the status contact of the CB is in the circuit. If it is part the main auxiliary stack switch in the breaker this change-of-state may be detected provided the contact makes during the trip-free operation. If a secondary auxiliary relay is used to multiply the breaker contacts, its contact may never fully change state because the breaker auxiliary contact did not make because the mechanism does not latch or it did not make for a long enough period of time for the auxiliary relay to operate before the circuit breaker trips. The third factor is the scan time of the RTU. RTU scan times vary due to the vintage of processor and the number of points being monitored. The RTU may not detect a change-of-state because it is has already changed again before it can be picked up by the next scan.

The third event occurs approximately two and one-half seconds after the second event began, as can be seen in Table 1, tripping the Bus 2 345kV and 115kV circuit breakers to lockout. The 2T345kV motor operated disconnects also tripped. The Bus 2 Overall Differential (OD) relay targets reported align with the CBs and MOD that operated for this event (Figure 6). Unfortunately there were no fault records captured for this event. Therefore, it is not clear if TR2 Overall Differential protection system operation was correct. However, at this point in the analysis it was assumed that the shield wire had jumped across to the Bus 2 side of the 1612 CB as a result of the flash created when the I161 CB reclosed into the fault resulting in the TR2 Overall Differential relay operation. This appears to be a valid assumption as it matched the sequence-of-events in Table 1. If the shield wire did jump across the 1612 CB as assumed the TR2 OD protective relay operation is proper.

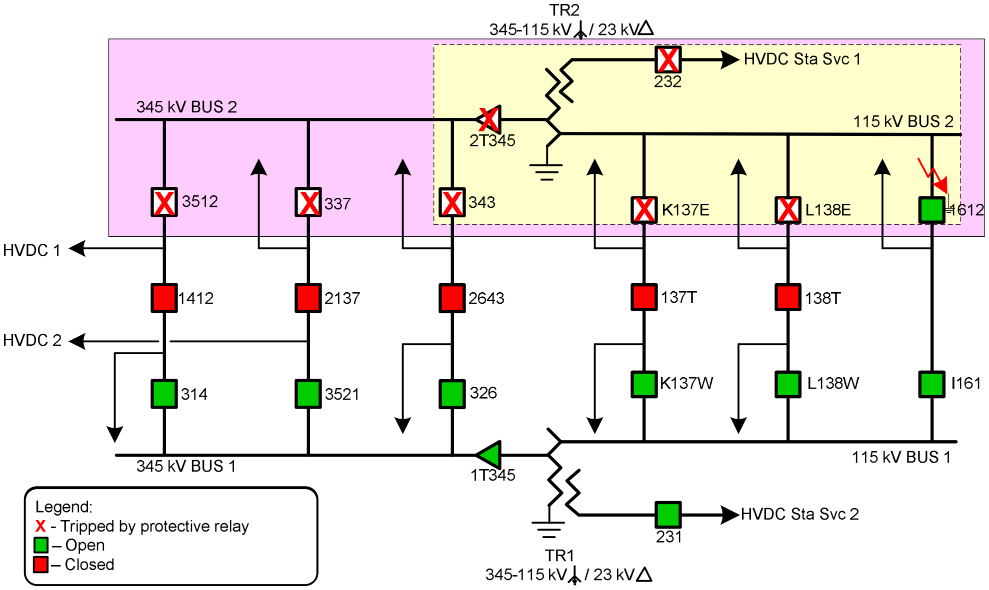


Figure 6 – TR2 Overall Differential Operation

Of concern for this event was the fact that the TR2 Overall Differential protection operated but the TR2 Transformer Differential protection did not operate as had occurred during event 2 when TR1 failed. The protection zones of the Overall Differential protection and Transformer Differential protection are highlighted in red and yellow respectively for reference in Figure 6. Another consideration is that the TR2 OD protection is an older solid state relay that may be susceptible to harmonics or a transient surge that resulted in the trip contacts being bridged causing the static protective relay to operate. Therefore, additional follow-up is required as it is still possible that this TR2 Overall Differential protection operation was improper.

The fourth event occurred as a result of the loss of HVDC station service from Sandy Pond. The loss of station service caused the HVDC Converter cooling pumps to shut down. The loss of the cooling pumps and the voltage rise of the DC filter capacitors caused a Bus 1 and 2 overvoltage condition initiating a Direct Transfer Trip (DTT) signal to Sandy Pond tripping the 1412 and 2137 CBs (Figure 7). The 3512 and 3521 CBs would normally trip when DTT is received, however, they were already open from the associated differential protection operations from the second and third event.

The design of the Transformer protection, which includes the Overall Differential and Transformer Differential relays, allows the 345kV Bus circuits breakers to reclose after the TR MOD opens. The fifth event in Table 1 is the auto-close of the 345kV breakers. As shown in Figure 1 the 326 and 314 CBs on Bus 1, and the 337 and 343 CBs on Bus 2 reclosed successfully and as can be seen in Table 1, Event 5 the change-of-state was detected by the RTU sequence-of-events recorder. The 3512 and 3521 CBs were driven to lockout when the DTT signal was received and could not reclose.

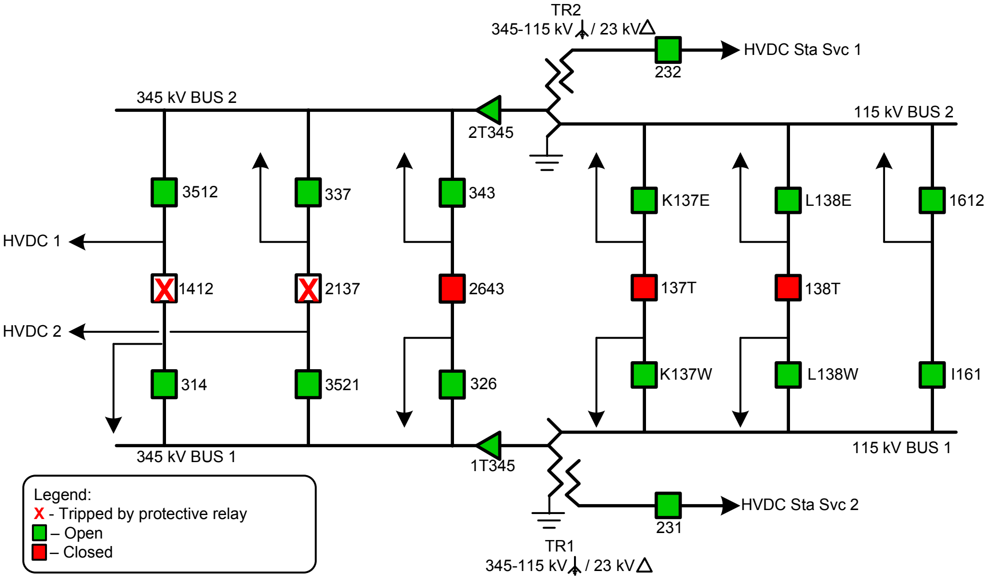


Figure 7 – Direct Transfer Trip Operation from HVDC

The analysis indicated that the protection systems operated properly for the cascading event. However, the operation of the TR2 Overall Differential protection was still in question because of the lack of a fault record to confirm the assumption that the shield wire jumped across the 1612 CB when the I161 CB reclosed into the fault. Was there another cause of the relay operation?

When reviewing the retrieved records, a swing record captured by one of the Sandy Pond DFRs during the event was found. Figure 8 is a view of the swing record showing the I161 reclose event and the Bus 2 trip event. Comparing the digital inputs with the C-Phase current a time line can be determined. The 326 and 3521 CBs change state with the first magnitude increase, which is when Transformer 1 failed. Measuring the time between the first and second magnitude increase, shown by the cursors, it can be seen in the lower right corner of Figure 8 the next event occurs 2.68 seconds later, at which time the 343 and 337 CBs, connected to Bus 2 trip. The 2.68 second time between the events is close to the difference in time between Event 2 and 3 in Table 1. The magnitude of the C-phase current for the second event in the swing record below is close to the 600-amp primary pick-up setting of the TR2 OD relay. This explains the OD operation, but why did the TR2 Differential protection not operate? A review of the relay setting records identified that the TR2 OD is set more sensitive than the TR2 differential relay. It was determined that there was not sufficient fault current to operate the TR2 Differential protection, therefore, the TR2 OD operation was proper.

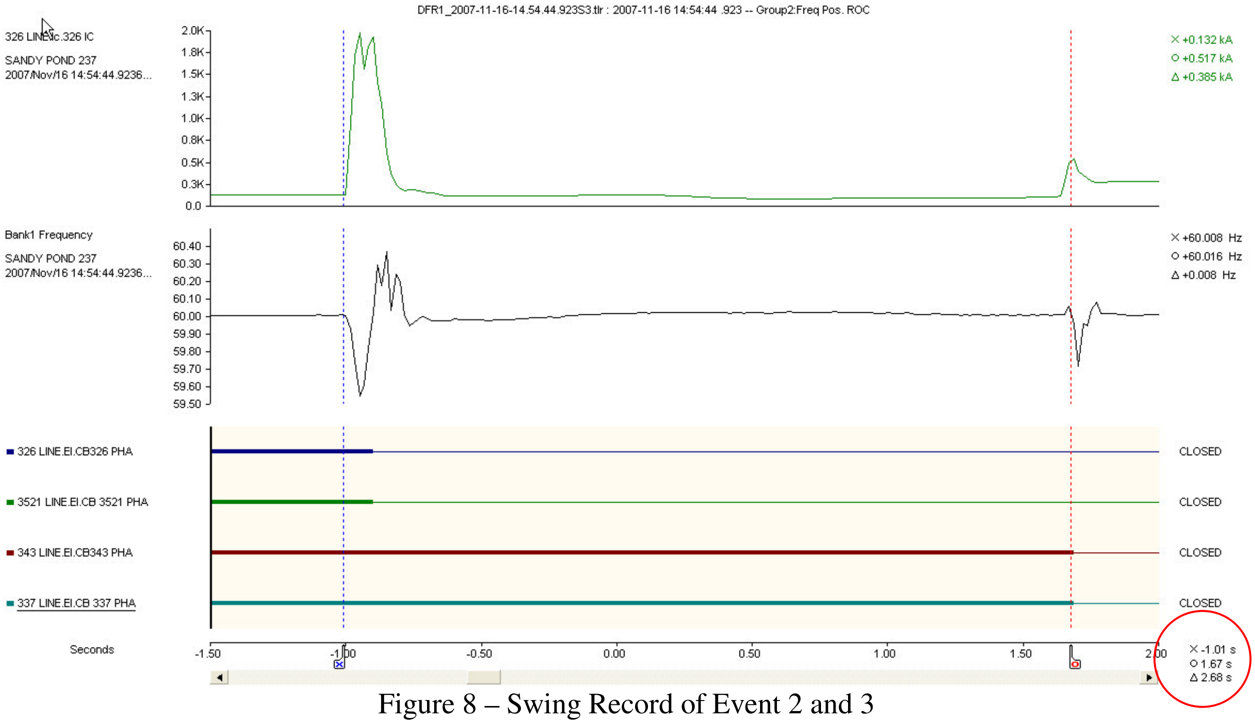


Figure 8 – Swing Record of Event 2 and 3

A physical inspection was performed concurrently with the fault analysis. Flash burns were found on the Bus 2 side of the 1612 circuit breaker to support the assumption that the shield wire jumped to the Bus 2 side of the 1612 CB when the I161 CB closed into the permanent fault. The arrows shown at the top of Figure 9 indicate the location of the shield wires and the arrows on the left side indicate where evidence of flash burns were found on the 1612 CB and the motor-operated-disconnects on the Bus 2 side of the 1612 CB. The results of the inspection confirmed the TR2 Overall Differential protection operated properly because the physical evidence and the data in the swing record agreed.

Figure 9 – I161 Line Bay (1612 CB foreground)

Based on the analysis and examination of the physical evidence it was determined that the protective relay schemes operated properly for the cascade event at Sandy Pond. Based on the analysis the event occurred as follows:

1. At 14:54:38 on November 16, 2007 the I-161 Line shield wire broke free of the structure in the Sandy Pond substation. The shield wire fell across the 1612 CB and came in contact with the line side bus between the I161 CB and 1612 CB causing a C-phase to ground fault. The I161 and 1612 tripped via Directional Distance Zone 1 protection.

2. The I161 CB reclosed automatically in 5 seconds into a permanent fault causing the I161 CB to trip on Instantaneous Overcurrent protection. Simultaneously Transformer 1 failed. Transformer 1 Differential Protection operated tripping and locking out the 345kV 314, 3521, and 326 CBs, the 115kV K137W, L138W, and I161 CBs and the 23kV 231 CB.

3. When the I161 CB closed into the permanent fault caused by the shield wire, the shield wire jumped and came into contact with the Bus 2 side of the 1612 CB causing a fault. The TR2 Overall Differential protection operated tripping and locking out the 345kV 3512, 337, and 343 CBs, the 115kV K137E, L138E CBs, and the 23kV 232 CB.

4. As a result of the operations, Sandy Pond HVDC converter terminal lost station service and shut down due to the loss of the cooling pumps. HVDC Bus 1 and Bus 2 Overvoltage Protection initiated a Direct Transfer Trip (DTT) to Sandy Pond tripping the 345kv 1412 and 2137 CBs. The DTT blocked closing of the 1412, 2137, 3512, and 3521 CBs.

5. The 1T345 Motor Operated Air Break (MOAB) and the 2T345 MOAB opened, which allowed the 345kV breakers to reclose. The 314, 326, 343, and 337 CBs closed automatically in 15

seconds. The 3512 and 3521 did not reclose because the DTT signal was still present from the HVDC terminal blocking breaker reclosing.

IMPACT OF EVENTS ON THE POWER SYSTEM

Sandy Pond substation is a major interconnection for power from northern New England and Quebec into the greater Boston metropolitan area. Although this disturbance involved multiple failures and faults (shield wire failure & jump, transformer failure) impacts to the transmission system was limited primarily due to proper operation of the protection systems. Automatic reclosing of the 345kV breakers at the end of the disturbance (Event 5) was particularly important to performance of the Boston area transmission system, limiting the interruption of power flow through the Sandy Pond substation to approximately 30 seconds. Had any of the protection systems mis-operated or reclosing of these circuit breakers been blocked, several major 345 kV lines might have remained out of service until system operators had an opportunity to assess the situation. During this time other transmission elements and protection systems might have been challenged, further degrading system reliability. One of the features of interconnected A.C. transmission systems is that disturbances can be detected at locations distant from the originating event. Examination of data recorded at substations remote from the faults can provide insight into the impacts that this disturbance had on the regional interconnection. What would have happened had a protection system mis-operated is difficult to determine but using data collected by disturbance recorders the impact of the event on the power system and protection system performance can be measured.

Power swings are oscillations of synchronous machines with respect to other synchronous machines. Power swings are caused by changes in load, switching, and power system faults. Protective relays must function properly during these power swings. When analyzing a power swing and the protective relay performance three factors must be considered. They are; Steady State Stability, Transient Stability, and the relay quantities encountered during the swing.

Steady state stability is the power systems ability to develop restorative forces in excess of the disruptive forces, such as a power system fault, that occur during an event. Transient stability is the systems capability to properly adjust to sudden large changes and remain in synchronism. How protective relays respond is based on the quantities encountered during these events.

To analyze the impact on system stability for this cascading event the swing records captured at Bear Swamp 230kV substation and Northfield 345kV substation were used. These two stations were chosen because each is a major intertie to New York. Power is typically exported to New York but during events where a loss of generation occurs, power flow typically changes direction and New York imports power to New England until the generation is restored.

The Northfield 345kV substation dynamic disturbance record data is plotted for 60 seconds, from approximately 20 seconds before initial fault (Event 1) through the automatic reclosing of the 345kV circuit breakers (Event 5). Figure 10 shows RMS voltage and frequency as calculated from the captured record at Northfield. The first four Events can be identified in the RMS voltage trace with a total voltage deviation of approximately 8 kV. These Events are more easily identified in the frequency trace, with frequency deviation caused by Event 4 dominating those caused by the fault during Events 1, 2 and 3. Event 5 cannot be identified in either voltage or frequency but was identified from the relative time after Event 4.

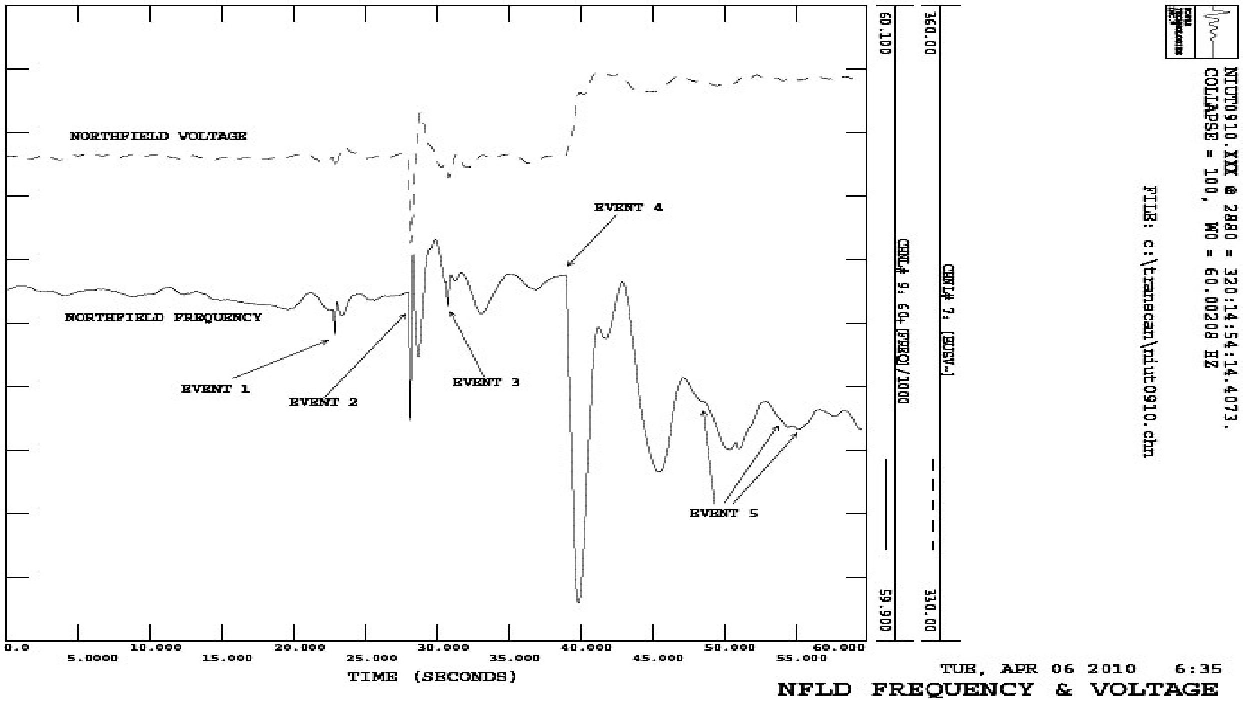


Figure 10 – Northfield Frequency and Voltage

Figure 11 shows MW and MVAR flow on the 345 kV line connecting New England to New York. The first four Events are readily identifiable in MW & MVAR flows, but not Event 5. While all power system quantities were affected, frequency and MVAR flow shows the events most distinctly.

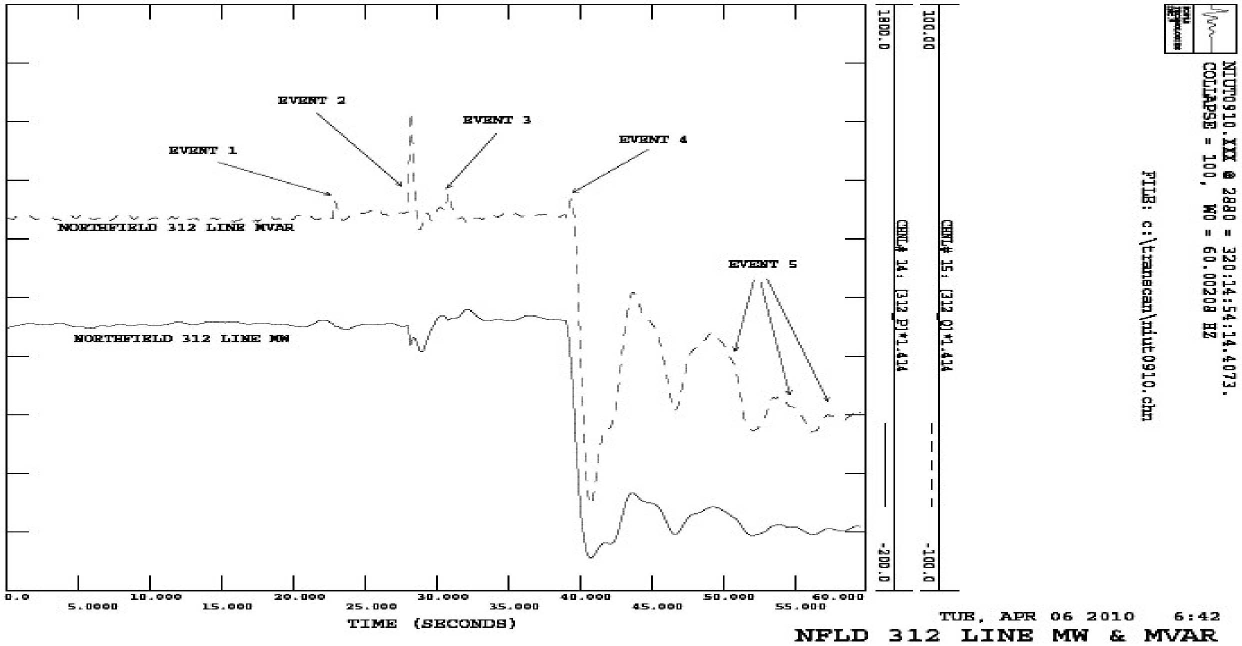


Figure 11 – Northfield 312 Line MW & MVAR Flow

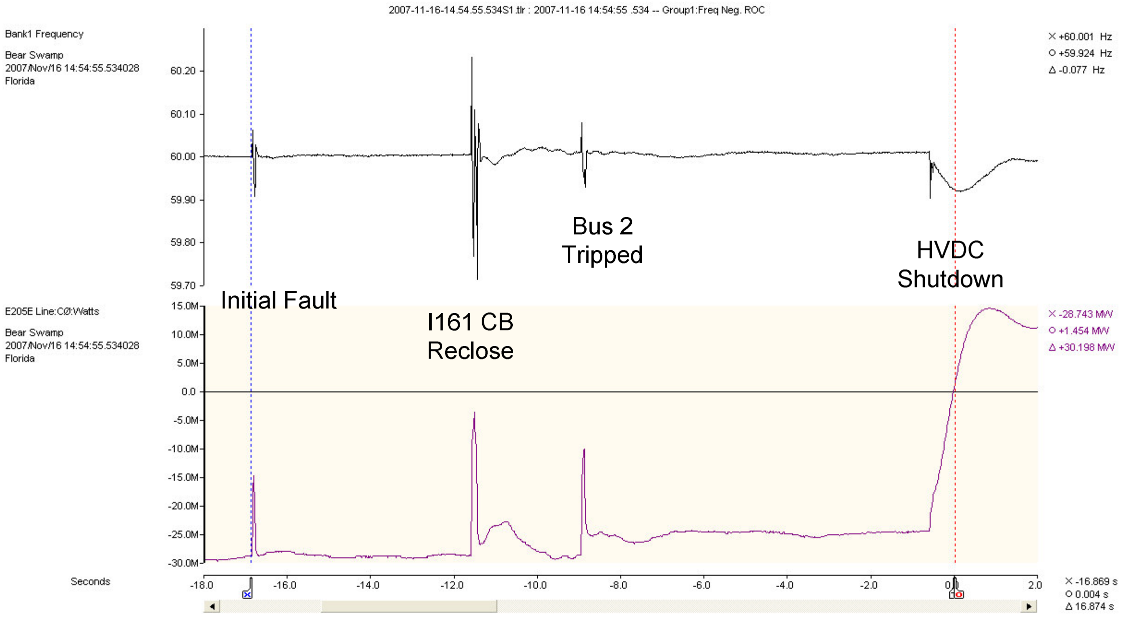


Figure 12 - Bear Swamp – Cascading Event Capture; Frequency and MW

The cascade event at Sandy Pond can also be analyzed with the Bear Swamp swing record shown in Figure 12 above. Referring to Figure 12 it can be seen that the initial fault caused a switching transient that momentarily impacted frequency and power flow. When the I161 circuit breaker (CB) reclosed a larger switching transient occurs and the system began to oscillate, as can be seen in the frequency plot. When Bus 2 tripped there was a smaller switching transient, and the oscillation continued but was damped. The oscillation continues to damp until the HVDC Terminal shuts down, when a new oscillation occurs and power flow changes direction, where New York is now importing power to New England.

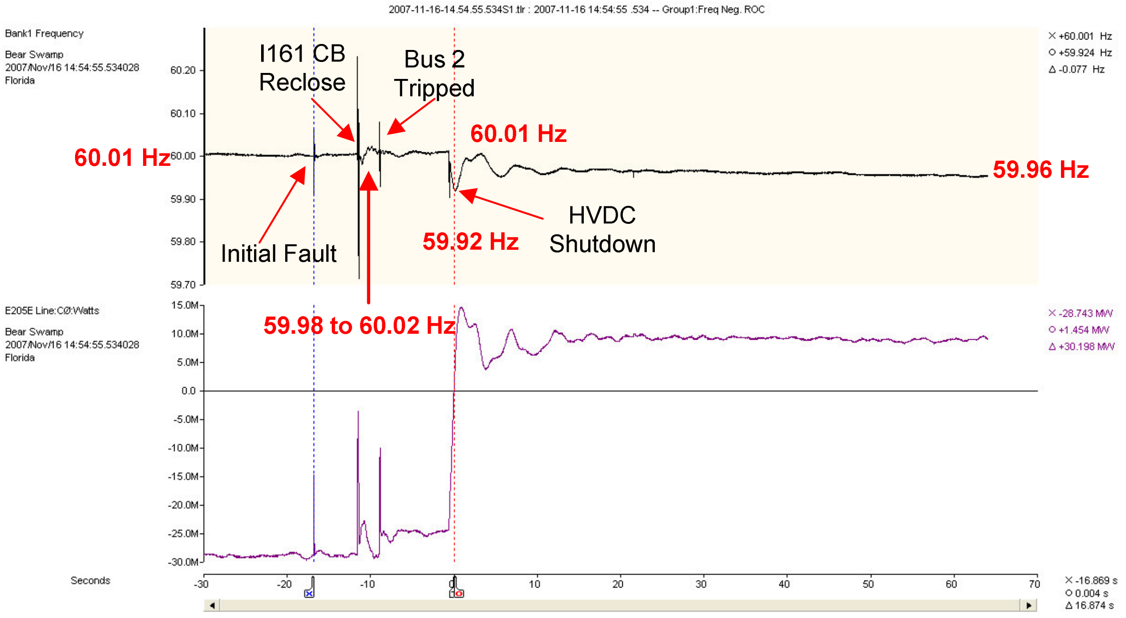


Figure 13 - Bear Swamp Intertie Swing Record

As discussed above the initial event did not have a significant impact on the system. The first oscillation occurred when the I161 CB closed into the permanent fault (Event 2). Referring to Figure 13 it can be seen the system frequency was stable at 60.01 Hz prior to the I161 CB reclose, with the exception of the switching transient which occurred during the initial fault. The system started to oscillate when the I161 CB reclosed. The initial oscillation ranged between 59.98 and 60.02 Hz and was damped through the Sandy Pond Bus 2 trip (Event 3). The second oscillation occurs when the HVDC Terminal shut down. The frequency oscillation ranges from 59.92 to 60.01 Hz and damps. The frequency then continues to decrease to 59.96 Hz at the end of the record.

While this disturbance was detected at remote locations, it did not cause any other equipment to operate. The loss of 1400 MW due to the loss of the HVDC supply did cause a decrease in frequency which was detected at Bear Swamp and Northfield. Based on the analysis the system had sufficient restorative resources to counter the disruption caused by the fault and was at steady state stability. The system also maintained transient stability as it recovered from the changes caused by the faults even though system frequency continued to decline. The last part of the analysis is to determine the impact the power swing had on protection system performance at Sandy Pond and Bear Swamp.

IMPACT OF EVENT ON PROTECTION SYSTEM PERFORMANCE

Proper operation of protection systems is critical to maintain system reliability. Protection systems must operate properly to quickly isolate faulted power system components to minimize damage to power system equipment, but more importantly other protection systems should not operate for a power swing unless that swing becomes unstable.

Power swings have caused impedance based protection systems to operate, typically when the power swing becomes unstable. The system impedance will vary during a swing and if the power swing becomes unstable the impedance of the system may pass through the impedance Zone 1 and/or Zone 2 distance protection, as shown in Figure 14. The protection system would operate, and this undesired trip could potentially initiate a wide area event.

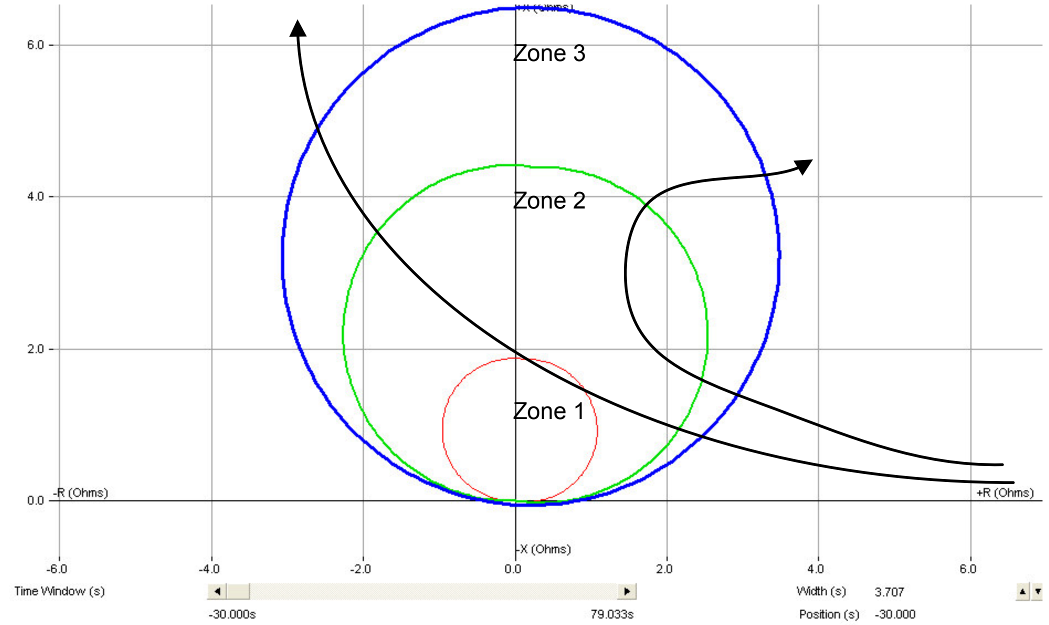


Figure 14 – Diagram of Swing Impact on Power System Protection

The R-X diagram is an effective method for evaluating impedance based protection system performance during an event by comparing the protection system measured quantities to the programmed relay settings. Impedance plots were done for two protection systems as part of the analysis.

The 343 Line remained in service through the entire event and plotting the apparent line impedance on an R-X diagram in relation to the protection system zones shown in Figure 15 allowed the 343 protection performance to be measured. Through the event the current magnitude on the 343 Line decreased to 103 Amps primary from 638 Amps primary and the voltage increased an average of 2 kV per phase. When reviewing the R-X diagram in Figure 15 it can be seen that the pre-fault load impedance was approximately 45 ohms primary and increased as the current on the line decreased. The quantities plotted are the same quantities measured by the relay. Based on this it was determined that the 343 Line Directional Distance protection responded properly for this event.

The E205E protection system at Bear Swamp was measured in the same manner as the 343 line protection system. The plot shown if Figure 16 shows the pre-fault load in quadrant III near the –R axis, with an apparent impedance close to 150 ohms. The post fault impedance moves into quadrant IV and is near 150 ohms but more reactive than the pre-fault impedance. Based on the impedance plot it can be determined that the E205E Line Directional Distance protection system performed properly for this event.

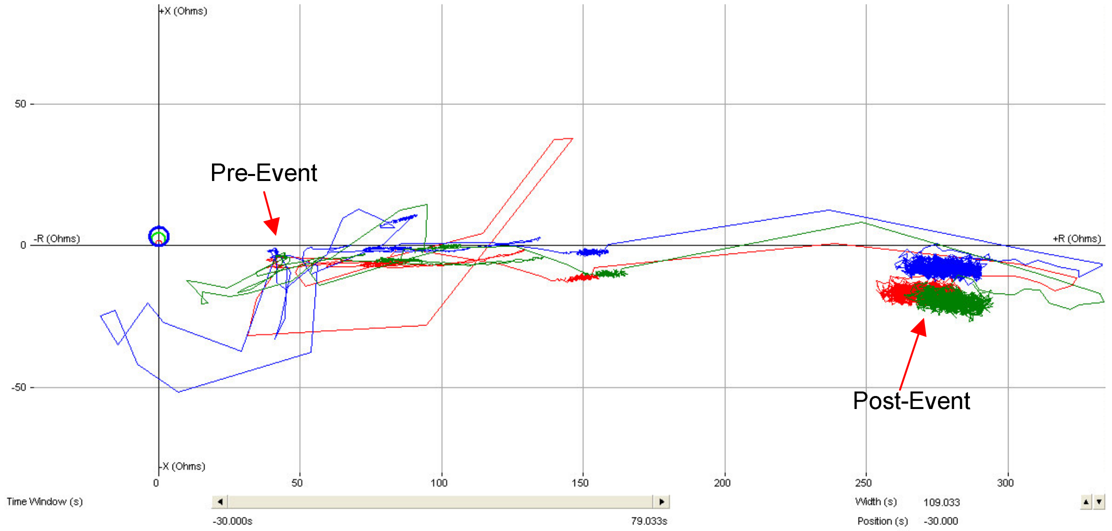


Figure 15 - Sandy Pond Swing Record – 343 Line Impedance Plot

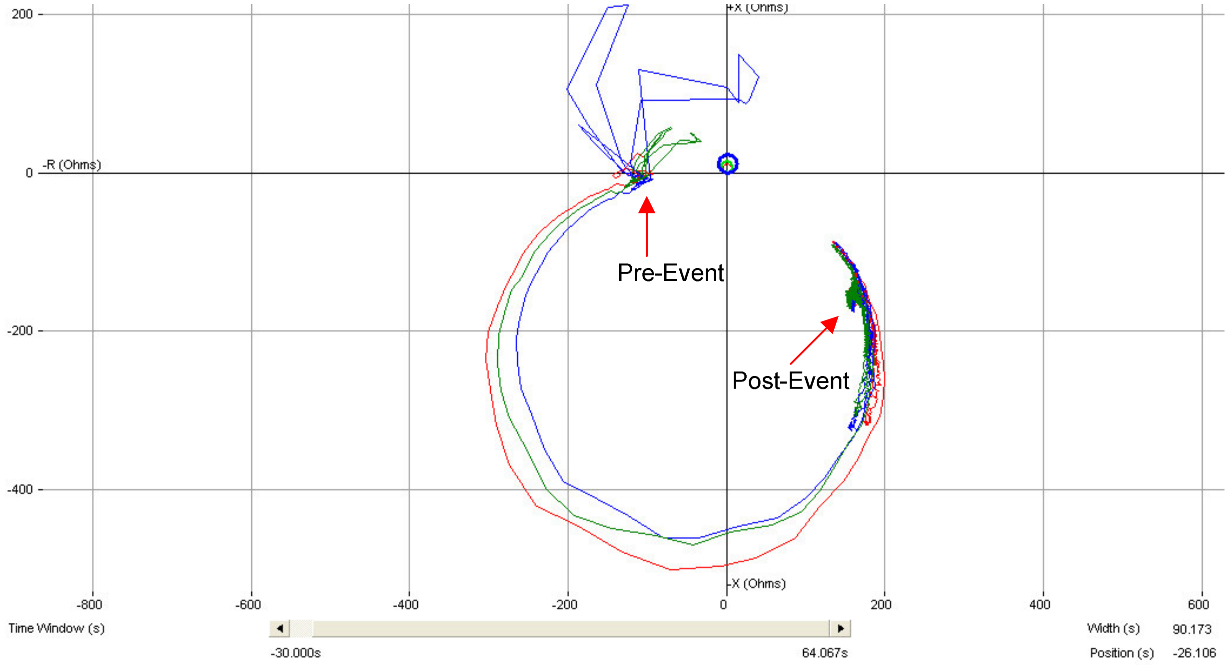


Figure 16 - Bear Swamp Swing Record – E205E Line Impedance Plot

CONCLUSIONS

The analysis of the cascading event at Sandy Pond utilized sequence-of-event, fault, and dynamic disturbance records to determine that all protection systems operated properly for the separate events that made up the cascading event. The protection engineer must use all the data and tools available to perform an analysis. A dynamic disturbance record was effectively used to evaluate the operation of the TR 2 Overall Differential protection system. A physical inspection of the Sandy Pond substation corroborated the results of the operational analysis.

This cascading event at Sandy Pond did not have a major negative impact on power system stability. The power swing records captured at Sandy Pond, Bear Swamp, and Northfield provided valuable information about the power system response and what occurred during the cascading event by evaluating system frequency, and by using the measured voltage and current from which power and impedance was calculated. The analysis indicates the system stability was at steady state, as there were adequate resources to recover from the disruptive forces created by the failed shield wire and transformer failure. The analysis also indicated that the system was able to stay in synchronism throughout the event and was therefore at transient stability.

The R-X diagram was used to evaluate the effect the power swing had on the protective relays providing a method of comparing the relays impedance settings to the power swing. The swing impedance did not enter the protection zones of the two protective relay systems evaluated. Using the R-X diagram to measure relay performance aids the protection engineer in understanding the impact power swings can have on protection system performance.

The protection systems at Sandy Pond operated properly isolating the faults, minimizing damage to the power equipment, and the reliability of the power system was maintained. Had any of the protection systems mis-operated the outcome may have been different. Analysis of events such as the cascading event at Sandy Pond provide the Protection Engineer and Regional Transmission Organization with valuable insight into how the system performs and can help to identify and correct potential problems that help make the power system more reliable.

REFERENCES

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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.

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David Bertagnolli joined ISO New England in 1985 and is currently a Principal Engineer in the System Operations Department. He is the technical lead for New England's Smart Grid synchrophasor project, monitors and analyzes transmission system disturbances and manages the interface between the ISO and nuclear power plants. Previously David worked at the Control Center for Con Edison Co. of New York and as a planning engineer for the American Electric Power company. He received a Bachelor's degree in Electrical Engineering from the University of Illinois and a Master's degree from Columbia University of New York. He is a registered Professional Engineer in the State of Connecticut and a senior member of IEEE.