Analysis of a Cascading Operation for Two Line Faults at National Grid

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Introduction

Two 115kV line fault events occurred in the same area within two (2) minutes that cascaded and resulted in two unexpected operations of three 115kV lines and the loss of a tapped off substation supply. Cascading operations are of concern to utilities and the Regional Independent System Operator (ISO). The protection schemes shall work properly to isolate faults quickly and minimize the impact on transmission system. This paper presents an analysis of the cascaded event utilizing fault records, from digital fault recorders and relays, and short circuit simulation to determine what happened and why the unfaulted lines operated. The fault records captured by disturbance monitoring equipment and the short circuit simulation provided valuable data which gave an insight into the nature of this disturbance. The fault records provided analog and digital data which allowed an efficient investigation and accurate analysis of this event.

Incident Summary

On August 05, 2010, the National Grid Control Center reported that:

- At 15:51:20 a lightning stroke caused a phase fault on the 115kV line 45 between Station A and B. Both of the A and B terminals of the 115kV line 45 tripped instantaneously. The line was successfully auto-closed at the Station A, but failed to auto-close at Station B.

- Two minutes and 14 seconds later (at 15:53:34), another lightning caused a C-phase-to-ground fault on the adjacent 115kV line 54, which links the B and C stations. The fault was located 10% of the distance from Station B. The faulted line was tripped from both terminals instantaneously by the line protection system and sent a Direct Transfer Trip (DTT) signal to Station E. Simultaneously, the line 46 directional ground instantaneous (DG Inst) relay at Station A sensed this 54 fault and sent a Direct Transfer Trip (DTT) signal to Station B. As a result, the line 46 over tripped on this close-in 54 fault at both terminals. The terminal A auto-closed successfully but the B did not auto-close (the same problem as mentioned above).

- One second (at 15:53:35) after the 54 fault, the 92 cable differential (LD) relays at Station D and E operated for an unknown reason, which blocked auto-closing on the 54 line terminals at B and C. The cable 92 was isolated at 21:01 for inspection. (Note: the cable 92 is tapped off the line 54 at the D station, 1.1 miles away Station B.)

- Approximately seven (7) hours after the original fault, the Control Center proceeded to isolate the cable 92 and transfer the load to the line 91. In the process of doing this, they had the operator turn the transfer switch at Station E to the "92 OUT" position. When this was done, the 91 Direct Transfer Trip (DTT) sent a trip signal to Station B and tripped the line 55 between Stations B and C at 22:53:36. This caused the E substation to go dead. This happened because the 92 LD lockout relay had not been reset and still had an initiate trip on the 91 DTT system. The DTT receivers then were turned off at Station E and B so that the 55 and the 91 lines could be restored. (Note: the line 91 is tapped off the line 55 at the D station, 1.1 miles away Station B.) Later that day, the 92 LD lockout relay was reset and the 91 DTT receivers were turned "on". The 92 cable was tested with no problem being found on August 7th, 2010.

The time of operations is listed in Table 1 and the line configurations are shown in Figure1. The 45 and 46 lines share a common right-of-way and the 54 and 55 lines share a common right-of-way. Relay targets reported for this event are as follows:

- Station A: 45 Line Permissive Overreaching Transfer Trip (POTT) keyed by Directional Distance Zone 2 (PODD) & Directional Distance Zone 1 (DD Zone 1)

  46 Line Directional Ground Instantaneous (DG Inst) & keyed a Direct Transfer Trip (DTT) signal to Station B

- Station B: 45 Line Permissive Overreaching Transfer Trip (POTT) keyed by Directional Distance Zone 2 (PODD)

  54 Line Directional Distance Ground Zone 1 (DDG Zone 1) &
  Directional Ground Instantaneous (DG Inst)

- Station C: 54 Line Directional Ground Instantaneous (DG Inst)

- Station D: 92 Cable Differential (LD)

- Station E: Direct Transfer Trip (DTT) signal received from Station B 54 Line
  92 Cable Differential (LD) & keyed a Direct Transfer Trip (DTT) signal to the Station B
  Keyed a Direct Transfer Trip (DTT) signal to Station B 55 Line

Table 1 – Time of Operations for 2010-08-05 Event
(Set t = 0 while the fault occurred at 15:51:20.160)

Time of Faults	Time of Operation			
15:51:20.160	t = 70 ms	Station A	45 & 45-3T CBs	TRIPPED
15:51:20.160	t = 70 ms	Station B	45 & 11-45 CBs	TRIPPED
15:53:34.560	t = 70 ms	Station B	54 & 33-54 CBs	TRIPPED
15:53:34.560	t = 70 ms	Station C	54 CBs	TRIPPED
15:53:34.560	t = 60 ms	Station A	46 & 3T-46 CBs	TRIPPED
15:53:34.560	t = 70 ms	Station B	46 & 22-46 CBs	TRIPPED
15:53:35		Station D	92 LD	OPERATED
15:53:35		Station E	92 LD	OPERATED
22:53:36		Station E	91 DTT	SENT to Station B
22:53:36		Station B	55 & 44-55 CBs	OPENED by 91 DTT
22:53:36		Station C	55 CBs	OPENED by 91 DTT
15:51:20.160	t = 5.07 sec	Station A	45 CB	AUTO-CLOSED
15:51:20.160	t = 10.07 sec	Station A	45-3T CB	AUTO-CLOSED
15:51:20.160	None	Station B	45 & 11-45 CBs	AUTO-CLOSE Failed
15:53:34.560	t = 0.44 sec [1]	Station B	54 CB	AUTO-CLOSE Blocked by 92 LD
15:53:34.560	t = 0.44 sec	Station B	33-54 CB	AUTO-CLOSE Blocked by 92 LD
15:53:34.560	t = 0.44 sec	Station C	54 CB	AUTO-CLOSE Blocked by 92 LD
15:53:34.560	t = 5.06 sec	Station A	46 CB	AUTO-CLOSE
15:53:34.560	t = 5.06 sec	Station A	3T-46 CB	AUTO-CLOSED
15:53:34.560	None	Station B	45 & 11-45 CBs	AUTO-CLOSE Failed

Note [1] the auto-closing was blocked at the time while the 92 LD operated at 15:53:35.000.

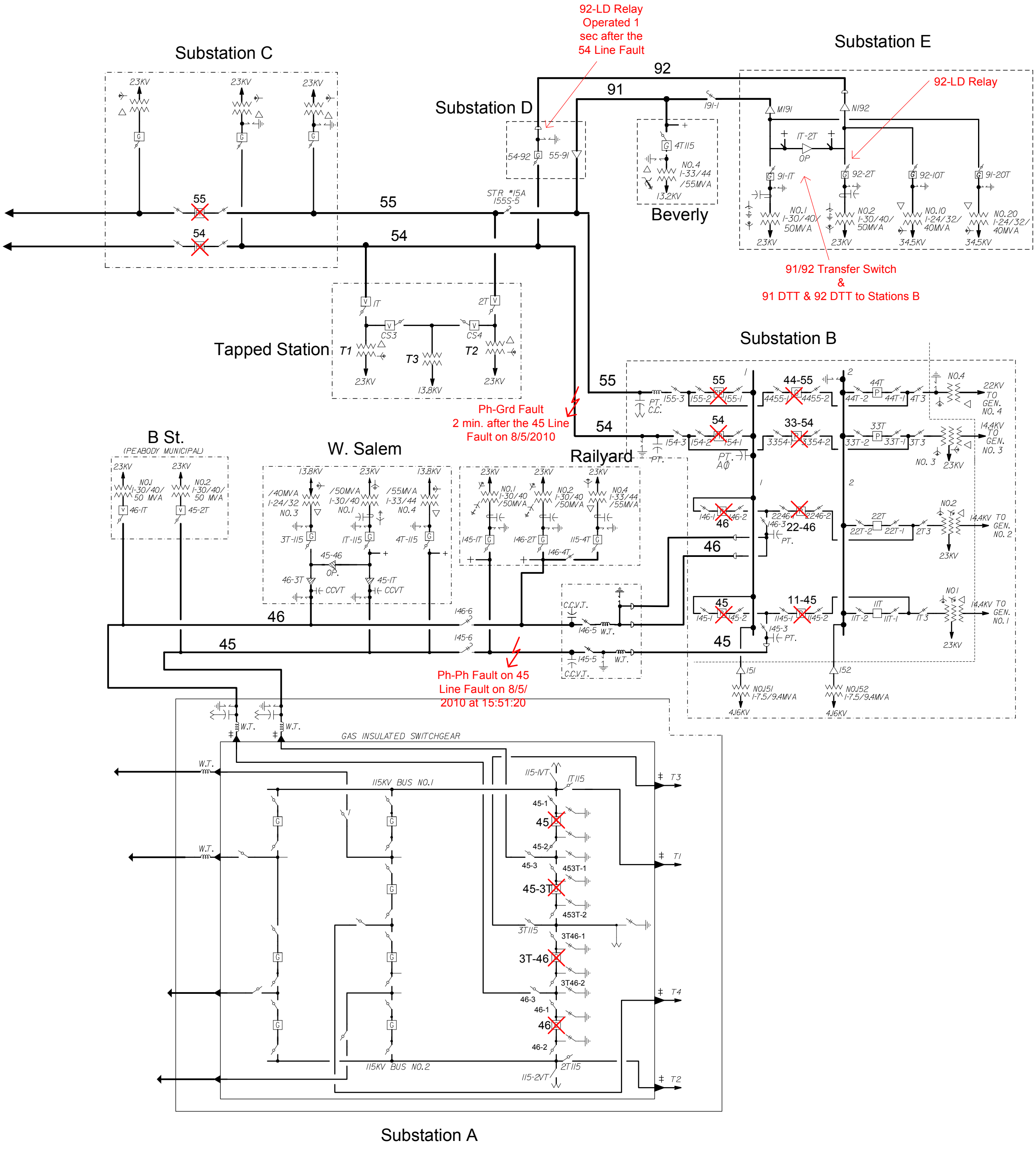


Figure 1. System One-Line Diagram with the 45 and 54 Line Faults

Investigation and Analysis

The first step of the investigation was to review relay targets, time of operations, and fault records from the digital fault recorders (DFRs) and the 45, 46 and 54 line relays at the A, B and C substations. Based on the reported relay targets, the time of operation (Table 1) and the fault records captured by the DFRs at the Stations A and B, it was confirmed that:

1. A phase fault occurred on the 45 line and the 45 line Permissive Overreaching Transfer Trip (POTT) scheme operated and isolated the fault correctly (Figure 2). The 45 line was successfully auto-closed at Station A, but failed to auto-close at Station B.

2. Two minutes and 14 seconds after the 45 line fault, later (at 15:53:34), a C-phase-to-ground fault occurred on the line 54 near Station B and the line 54 directional ground instantaneous (DG Inst) and the directional distance ground zone 1 (DDG Zone 1) relays at Stations C and B, respectively, operated and isolated the 54 line fault correctly (Figure 3B). As per design, the 54 line protection also keyed a Direct Transfer Trip (DTT) signal to Station E correctly. Simultaneously, the line 46 directional ground instantaneous (DG Inst) relay at Station A sensed this 54 fault and sent a Direct Transfer Trip (DTT) signal to Station B. As a result, the line 46 over tripped on this close-in 54 fault at both A and B terminals (Figure 3A and 3C). The A terminal auto-closed successfully but the B terminal did not auto-close.

3. One second (at 15:53:35) after the 54 fault, the 92 cable differential (LD) relays at Station D and E operated for the external 54 line fault for an unknown reason, which blocked auto-closing on the 54 line terminals at B and C.

4. Approximately seven (7) hours later, during isolating the cable 92 and transferring load to the line 91 at Station E, the 91 line Direct Transfer Trip (DTT) incorrectly sent a trip signal to Station B and tripped the line 55 between Stations B and C. This caused Station E to go dead.

Based on the findings described above, the investigation focus then moved to identify why the 45 and 46 breakers at Station B failed to auto-close, the 46 line at Station A over tripped, the 92 cable differential relay operated on the through fault and the 91 line Direct Transfer Trip (DTT) incorrectly sent a trip signal to Station B.

What caused the failure of synchronism check supervised auto-reclosing on the 115kV Breakers at Station B? The auto-closing scheme on the 115kV line breakers at Station B is supervised by a synchronism check function, which monitors the voltage phase angle, called as synchronism check angle, across the open breaker. During the investigation, it was noticed that the synchronism check angle for auto-closing on all of eight 115kV breakers 45, 11-45, 46, 22-46, 54, 33-54, 55 and 44-55 at this station was set at 10 degrees in 2004, that seems narrow since it is typically set around 25 to 30 degrees in National Grid. To quantitatively verify this, Transmission Planning Department was consulted and some Generator Shaft Torque simulations were conducted regarding the Synchronism check angle at Station B. The results concluded that:

1. The voltage angle across the 45 or 46 open breaker at Station B should not exceed 10 degrees as long as all other lines in the area (e.g. 45 or 46, 54 and 55) are closed in. However, the angle does get close to 10 degrees (the simulation shown 9.1 degrees at shoulder peak load) with all generators running at Station. No shaft torque problems at Station B were seen from the switching event on August 05, 2010. However, if the 46 line is open at the same time as the 45 breaker opens and closes, then the angle across the 45 open breaker approaches 25 degrees. This subjects one of the generators at Station B to an 81% of shaft torque (i.e. % of MVA nameplate). The IEEE recommended maximum is 50% of nameplate MVA. Note however that this constitutes an

"unplanned" switching event (opening and closing the breaker 45 while the breaker 46 is open); therefore, this is not in opposition to the IEEE recommendation. It is recommended to open up the synchronism check setting to 20 degrees that should provide enough margins to close the 45 breaker with the 46 line in-service, while at the same time providing a level of safety when the 46 line is our of service and the 45 breaker trips and attempts to auto-close (Figure 1).

2. The voltage angle across the 54 or 55 open breaker at Station B can exceed 10 degrees, even when the parallel line is in-service and closed through. When the parallel line is out of service, the angle can approach 25 degrees. However, in both cases, the Shaft Torque does not come close to 50% of nameplate for any of Station B units. Therefore, it is recommended to open up the synchronism check setting to 30 degrees for the 54 and 55 breakers (Figure 1).

Further review of the fault records on August 05, 2010 showed that the voltage phase angle across the 45 open breaker at Station B was 11.4 degrees even though the 46 line was in-service and so the breaker did not reclose, which is larger than the setting of 10 degrees. That double proved the Generator Shaft Torque simulation results and explained why the 45 breaker failed to auto-close at Station B during the 45 line fault.

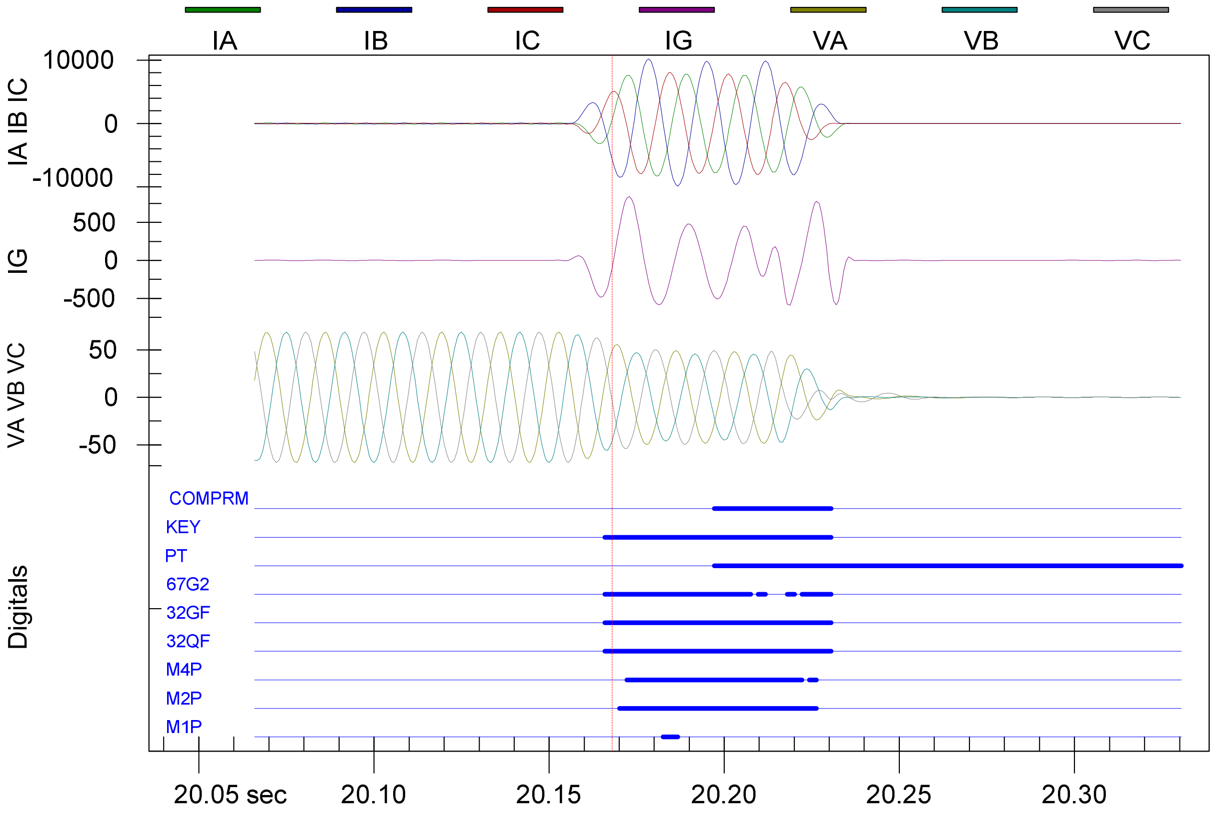
Why did the 46 directional ground instantaneous (DG Inst) relay at Station A respond to the 54 line fault? The pickup of the 46 DG Inst relay at Station A was set based on taking out one of the largest contributions, line or generator, (i.e. the N-1 philosophy of the National Grid). However, prior to the 54 fault, at Station B one of the generator unit was out of service and the line 45 was open due to the auto-closing failure as mentioned above. The 54 fault occurred two minutes and 14 seconds after the line 45 went out. By simulating the fault and reviewing the records, it was verified that:

1. The 46 DG Inst relay would not see external faults if only any one component out. In another word, if the system is under the N-1 condition. That implied that the pickup setting of the relay was proper as per the company protection application philosophy.

2. Due to both of an unit and the line 45 out of service at the time, the 46 DG Inst relay sensed the fault current was about 25% higher than only one component was out and it was just above the pickup value. As a result, the relay over tripped the line 46 at Station A and initiated a direct transfer trip (DTT) signal to Station B and tripped the 46 terminal over there. Given that the 46 DG Inst operation was correct but undesired.

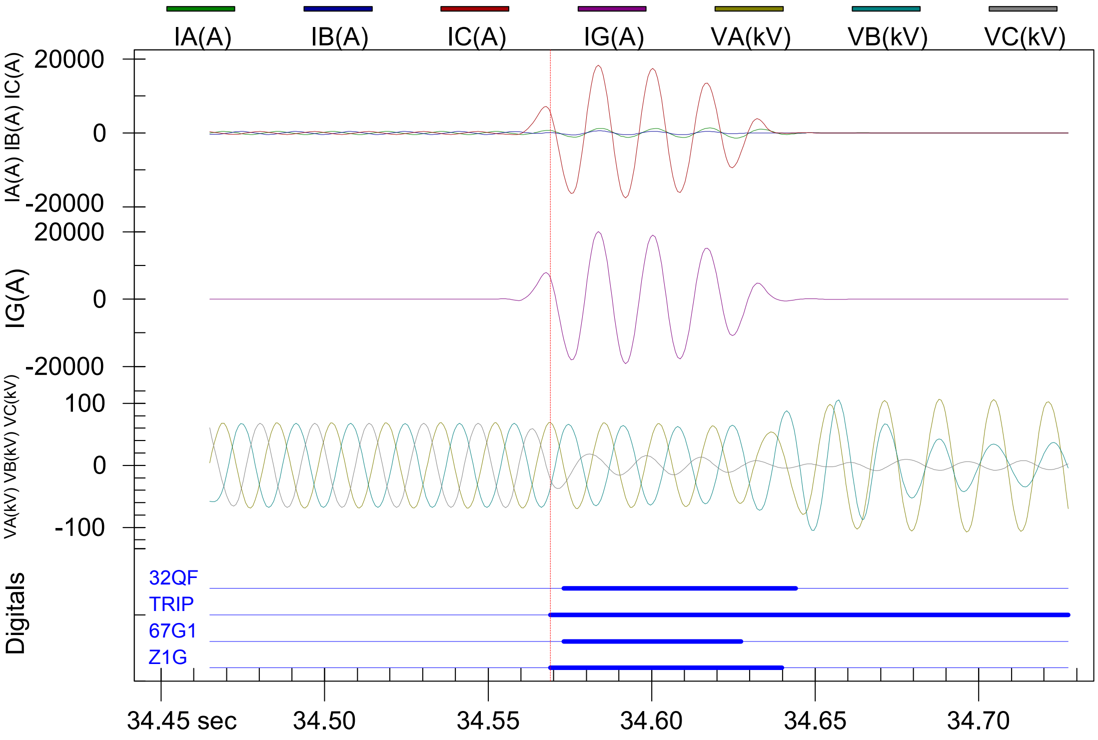
Why did the 92 cable differential (LD) scheme between Stations E and D operate on the 54 fault? Based on the manufacturer's recommendation, this 92 LD phase bias had been set at 1.0 Ampere since 1996. While, a revised application note from the manufacturer was received in 2007, in which it was suggested to reset the phase bias at 2.0 Amperes or higher to insure that the line differential relay provides the optimum level of security without sacrificing dependability. Too low phase bias setting may compromise security for CT errors during external fault with high fault current as per the manufacturer. Give that it is very likely that the 92 LD relay operated on the through 54 fault because of the sensitive phase bias setting (Figure 1).

The last question is **what caused the 91 direct transfer Trip (DTT) sent a trip signal to Station B and tripped the 55 line between Station B and C during transferring load to the line 91 at Station E?** As per the design at Station E, in the process of transferring the load to the line 91 at this station, first the 92 cable differential (LD) lockout relay should have been reset manually and then turned the transfer switch from the "NORMAL" to the "92 OUT" position. Unfortunately, the 92 LD lockout relay had not been reset yet when the transfer switch was turned to the "92 OUT" position. This resulted that there was still an initiate trip path on the 91 DTT circuit. Therefore, the 91 DTT was initiated and sent a transfer trip signal to Station B and C. The above finding and a further review of the schematic design on the transfer scheme concluded that there is no design error for the 92 and 91 transfer scheme at Station E, but there was an improper operational procedural during the transfer, which caused the initiation of the 91 DTT.



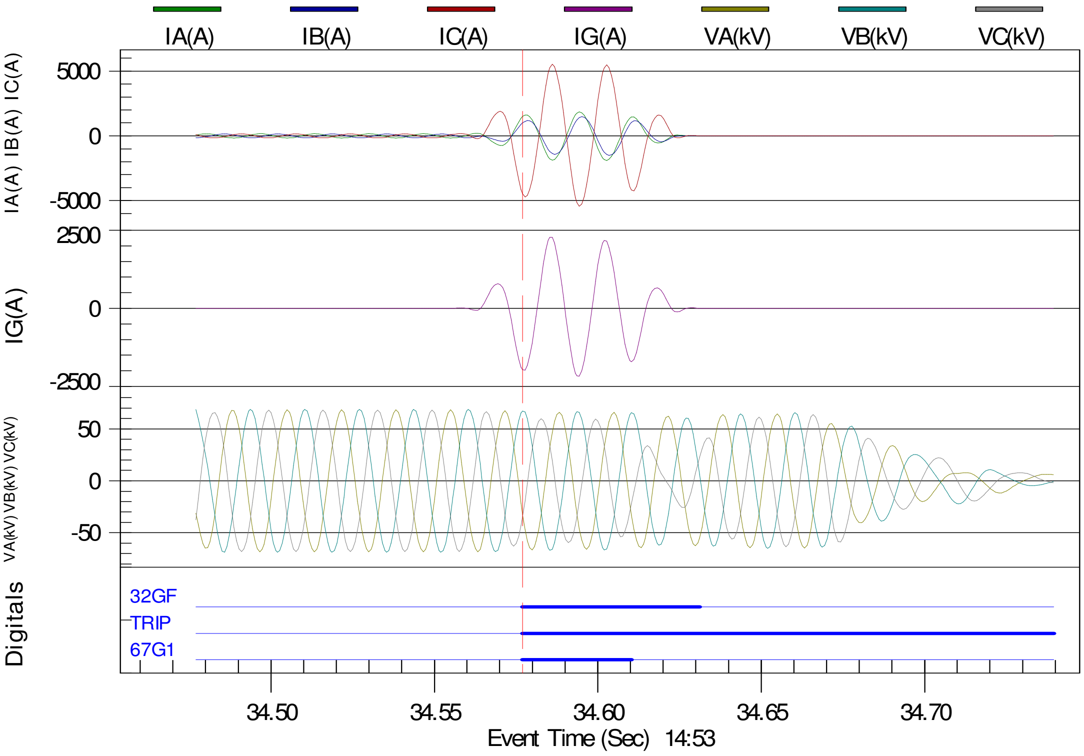
Note: COMPRM = POTT Trip; M1P = DD Zone 1

Figure 2. 45 Line Relay Waveforms at Station A on 08/05/2010 @ 15:51:20



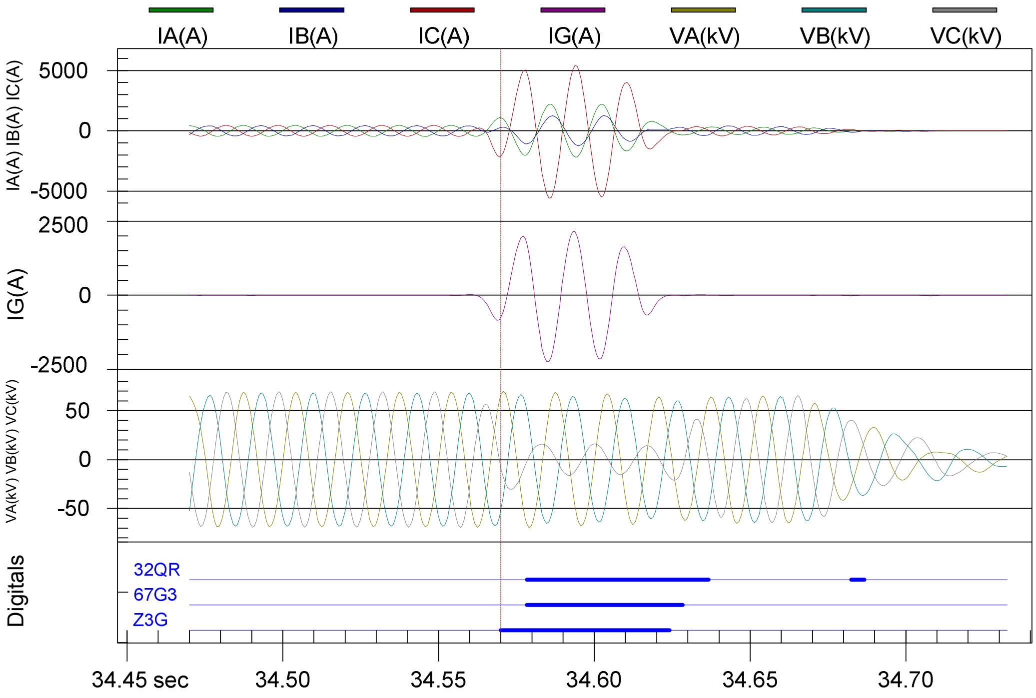
Note: Z1G = DDG Zone 1; 67G1 = DG Inst

Figure 3A. 54 Line Relay Waveforms at Station B on 08/05/2010 @ 15:53:34



Note: 67G1 = DG Inst

Figure 3B. 46 Line Relay Waveforms at Station A on 08/05/2010 @ 15:53:34



46 Line tripped at Sation B by 46 DTT from Station A

Figure 3C 46 Line Relay Waveforms at Station B on 08/05/2010 @ 15:53:34

Lessons Learned and Conclusions

As a result of the investigation, four (4) recommendations were made:

1. Based on the National Grid Transmission Planning's recommendation, reset the synchronism check angle from 10 to 20 degrees for the breakers 45, 11-45, 46 and 22-46 and to 30 degrees for the breakers 54, 33-54, 55 and 44-55 at Station B.

2. Based on the manufacturer's recommendation, reset the phase bias from 1.0 to 2.5 Amperes for the 92 cable differential relays at both of Station D and E.

3. To prevent similar procedural error from happening again, the design of 91/92 Transfer Switch at Station E was modified to not allow the 92 cable differential (LD) lockout relay to trip the 91 line regardless of the position of the Transfer Switch. The change was completed at the substation ten days after the event. However, it is still necessary to reset the 92 LD lockout relay, if operated, and turn off the DTT receivers at both D and E substations on the out of serviced line once the cable 92 is isolated.

4. Although National Grid does not normally set relay with considering N-2 condition, to be more secure, it is suggested to raise Station A line 45 and 46 directional ground instantaneous pickup value with considering two components out of service to prevent from over tripping for any external faults since one of the generation unit is off for most of time as confirmed with the owner.

Yujie Irene Lu has been employed in Protection Engineering at National Grid since 1990. She is a principal engineer in the Department of Protection Standards and Support, where she analyzes system disturbances on transmission and supply networks, performs system analysis for short circuit conditions, develops/revises transmission and distribution protection and control system standards and guidelines, designs protection systems on a conceptual basis, specifies equipment and determines protection settings and logics. Since mid 90s, she has been developed testing files for microprocessor relays for providing support to the field testing group and enhancing the quality of protection system testing procedures. She has 20 year's experiences as a lead protection engineer on projects and worked on installation of two major 345/115kV GIS transmission substations in National Grid recently. She led the development of standardized directional comparison blocking (DCB), loss of potential (LOP) and switch onto fault (SOTF) schemes for internal use. Previously, Irene worked for the Department of Energy of China for 5 years and for the Beijing Power Company for 2 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. She received the 2010 Outstanding Engineer Award from the Boston Chapter of the IEEE Power and Energy Society in November 2010.

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References:

1. RFL-9300 Instruction Manual

2. Bias Setting Guidelines and Examples for RFL 9300 - Application Note: AN 9300-001, Date: 9/15/2002

3. Schweitzer SEL-421 Reference Manual