Analysis of SOTF Scheme Operations for Adjacent Line Faults At National Grid

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Introduction

Analysis of switch onto fault (SOTF) operations present unique analytic challenges due to the lack of time aligned data for both analog and digital signals. The use of microprocessor relays for the SOTF function, and especially the data they provide, enables a much more thorough analysis of these types of events. Three (3) SOTF operations occurred recently at National Grid substations, interrupting service to customers and impacting system reliability – a major concern for the Regional Transmission Operator ISO New England. This paper examines the three SOTF operations using data captured by digital relays and sequence of events recording equipment. It will be shown that this type of data provides important insight into the nature of these events and greatly facilitates efficient investigation and accurate analysis.

Case One:

Incident Summary

Eve substation is supplied by two 115kV transmission lines, line 7 from Mys substation and line 8 from Mwd substation, separated by an in-line 115kV circuit breaker 8-7. Two wye-wye-grounded with tertiary 115kV/23kV/4kV step-down transformer banks and two delta/wye-grounded 115kV/13.2kV step-down transformers connected to each 115kV line via airbreaks. The substation and faulted line configuration are shown in Figure 1.

On April 22nd, 2011, the National Grid Control Center reported that:

At 08:06 AM, contractors were working on the 23 kV cable duct banks and broke a guy wire which wrapped on the 115 kV line 7, causing a close in B-to-C-Phase fault at Eve substation. The line 7 protection operated properly at both Eve and Mys substations, which tripped the 115kV in-line breaker 8-7 and de-energized the 23kV, 13kV and 4kV bus #1, i.e., half of the supply to the Eve substation. However, simultaneously the SOTF function of the adjacent line 8 protection also operated, causing loss of the other half of the substation's supply. This in turn caused all 23kV, 13kV and 4kV bus breakers at the Eve substation to trip, which then created an overload condition on the 23kV network in the area, resulting in the loss of a large number of customers. Relay targets reported at Eve and Mys substations for this event are as follows:

Eve:	Line 7 Directional Distance Zone 1 B and C Phases (DD Z1) Line 8 Switch Onto Fault (SOTF)
Mys:	Line 7 Directional Distance Zone 1 B and C Phases (DD Z1)

Investigation and Analysis

Care must be taken when energizing a line that has been out of service or reclosing a line that has been tripped with a protective relay because the line may have a fault on it. The Switch-Onto-Fault (SOTF) protective function, sometimes called Dead-Line-Pickup (DLP), is provided to detect close-in-phase-faults upon energizing or reclosing into a line. In these situations, there is no voltage present (if the line uses line voltage transformer for voltage sensing) to provide a "memory" to the line distance function, so the line distance function cannot detect a fault. The SOTF function is in-service for a short time after the line breaker, breaker 8-7 in this case, is closed allowing phase overcurrent (50L) to detect the fault. Figure 2 illustrates the circuit breaker SOTF logic for line 8 at Eve substation.

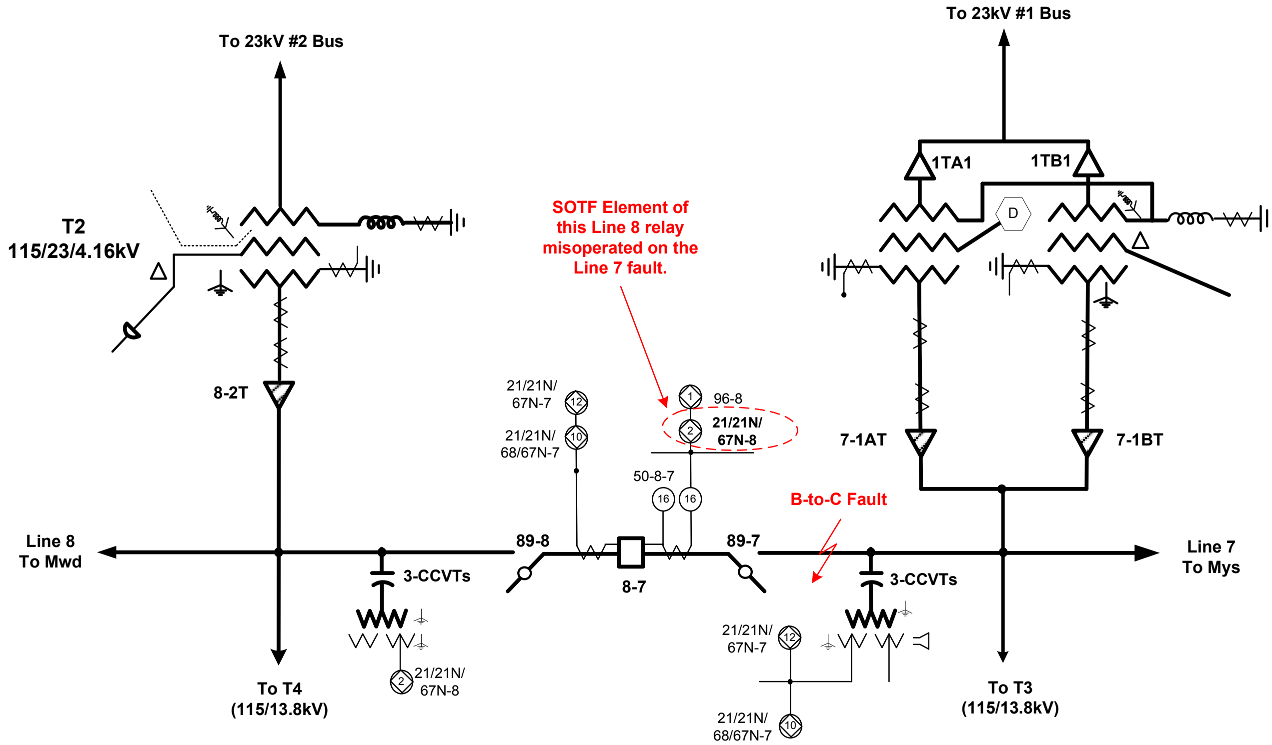
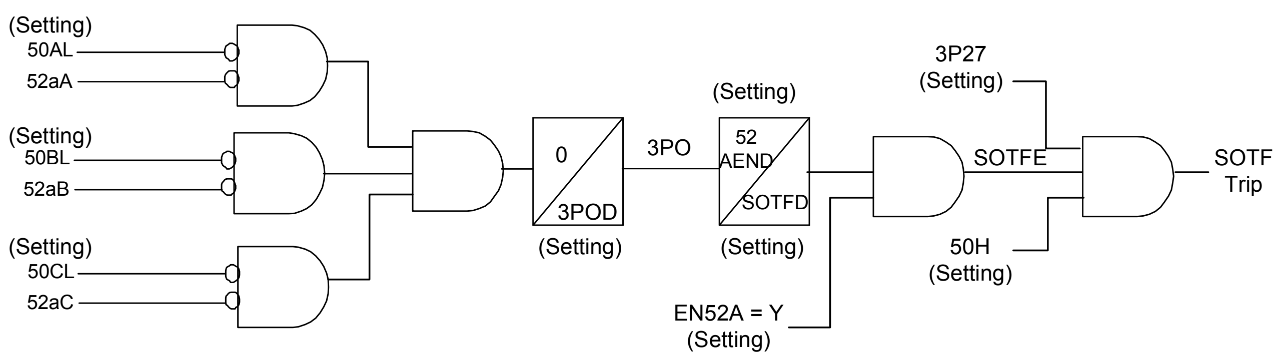


Figure 1. Eve Substation 115kV One-Line Diagram



52aA, 52aB & 52aC – Breaker Normally Open contact
50AL, 50BL & 50CL – Phase overcurrent supervision
3POD, Three-Pole Open Delay – Security time delay for dissimilar breaker pole closing
52AEND, 52a Enable delay – Sets minimum time after all breaker poles open before activating SOTF logic
SOTFD, SOTF Time duration – Sets how long SOTF function in-service after the breaker is closed
SOTFE, SOTF logic enabled – Enables three-phase SOTF tripping
50H, Phase overcurrent pickup
3P27, Three-phase undervoltage conditions

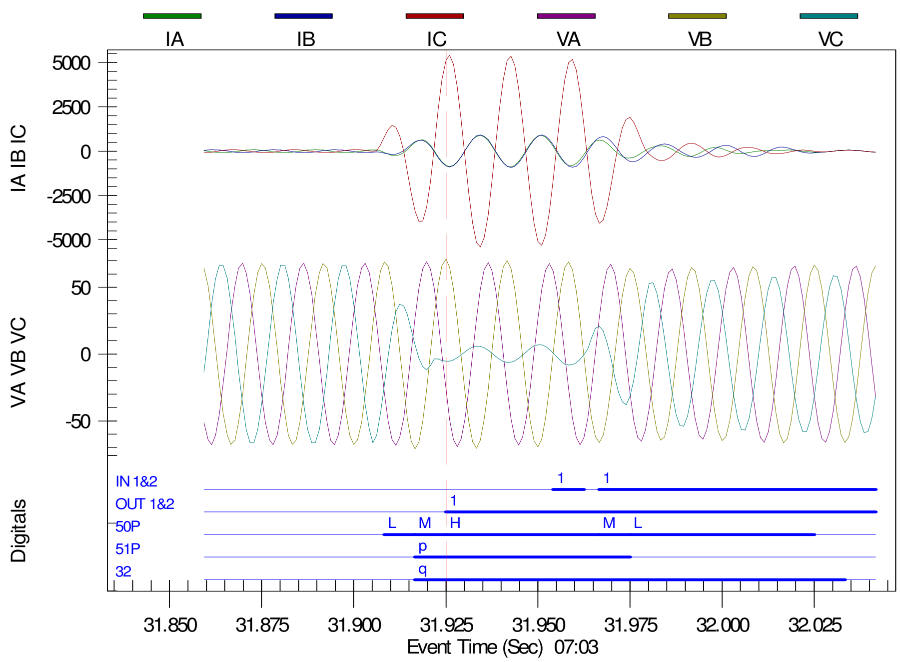
Figure 2. Eve Substation Line 8 Circuit-Breaker-Opened Switch-Onto-Fault (SOTF) Logic

Refering to Figure 2, once the breaker is open, the logic bit 3PO asserts after the 3POD dropout time. When the breaker closes in, the 3PO deasserts after the 3POD dropout time and the relay continues to assert the logic bit SOTFE for dropout time SOTFD. In other words, SOTF enables for the period of dropout time of SOTFD. If a fault exists on the line and the breaker closes or recloses into the fault, the fault detector of 50H and three-phase undervoltage sensor of 3P37 will pick up. As a result, the logic bit SOTF Trip asserts and issues a trip command.

The first step of the investigation was to collect and review relay targets, sequence of event and fault records captured by the line 7 and line 8 relays at Eve. Based on the reported relay targets and the captured fault records, it was confirmed that:

- The phase directional distance zone 1 function (DD Z1) out of the faulted line 7 relaying sensed the fault and correctly tripped the 115kV in-line breaker 8-7 as well as the 23kV, 13kV and 4kV bus #1 breakers.
- The switch-onto fault (SOTF) function out of the adjacent line 8 responded to the fault and also operated before the contact of the breaker 8-7 was physically open.

Why did the SOTF function of the adjacent line 8 protection respond to the close-in fault on the line 7 at Eve substation? Prior to the fault, the breaker 8-7 was at closed position, however, the line 8 relay record indicated that the breaker 8-7 normally open contact was deasserted, i.e. the breaker was indicated at open position (see digital input IN1 in Figure 3 in detail). Based on this finding, the input and output wiring of the line 8 relay was checked and discovered that, instead of a normally open contact (52a), a normally closed auxiliary contact (52b) of the 8-7 breaker was wired into the line 8 relay. As a result, the logic bit SOTFE was already asserted at the moment of fault occurred. As soon as the fault detector 50H and undervoltage sensor sensed the fault, the logic bit SOTF Trip picked up and caused the improper operation on the line 8 relay.



IN1 – Breaker 8-7 auxiliary contact; OUT 1 – Trip Output

Figure 3. Line 8 Relay Fault Record at Eve Substation on 04/22/2011

Case Two:

Incident Summary

Wild substation is supplied by two 115kV transmission lines, line 9 from Shill substation and line 6 from Hartford substation, separated by two in-line 115kV circuit breakers 9 and 6. A delta/wye-grounded 115kV/13.8kV step-down transformer is connected between the two 115kV in-line breakers. The substation and faulted line configuration are shown in Figure 4.

On March 20th, 2011, the National Grid Control Center reported that:

At 14:42 AM, a blown C-Phase lightning arrestor caused a closed-in C-phase-to-ground fault on 115kV line 9 at Shill substation #1 transformer. The 115kV in-line breaker 9 at Shill tripped by the line 9 relay. However, the in-line breaker 9 at the line's other terminal at Wild did not trip but the in-line breaker 6 adjacent to the breaker 9, was over tripped by the SOTF (or called Dead Line Pickup) function for the line 6 protection at Wild. Relay targets reported at Shill and Wild substations for this event are as follows:

Shill:	Line 9 Directional Distance Ground Zone 1 (DDG Z1) & Directional Ground Inst (DG Inst)
Wild:	Line 6 Dead Line Pickup (or called as Switch-Onto-Fault – SOTF)

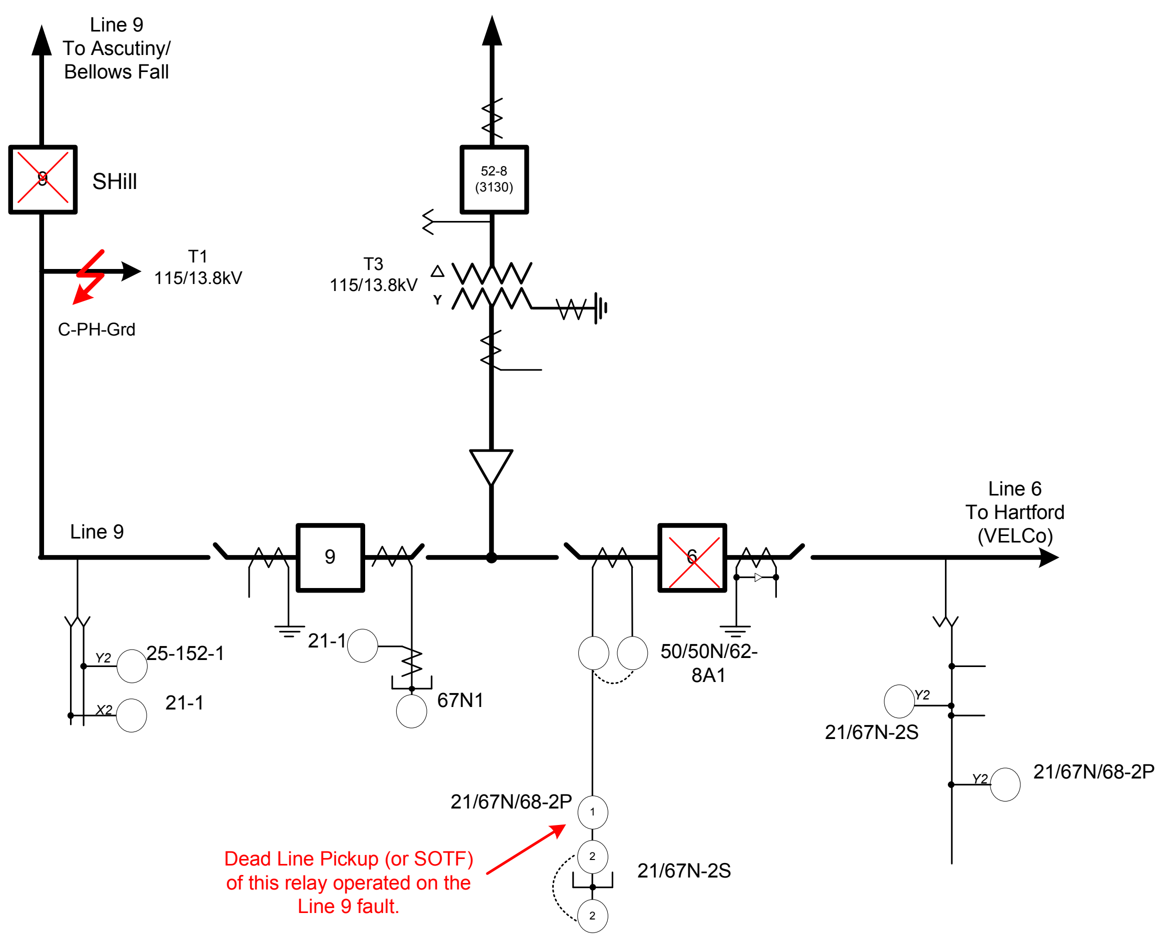


Figure 4. Wild and Shill Substation 115kV One-Line Diagram

Investigation and Analysis

The SOTF function of the line 6 relay at Wild uses voltage and current to determine whether the line is energized. How the SOTF logic of the line 6 relay actually works at Wild substation is illustrated as follows:

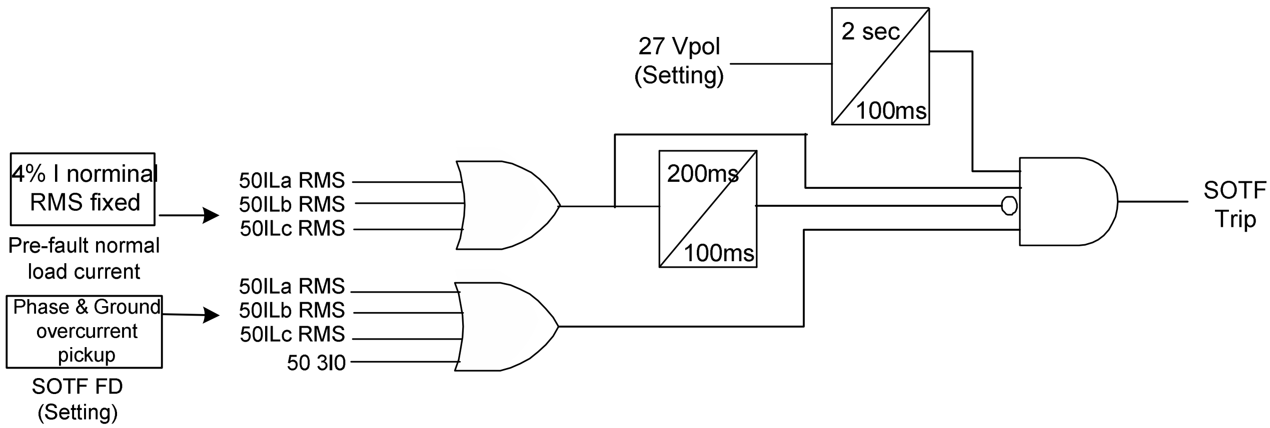


Figure 5. Wild Substation Line 6 Switch-Onto-Fault (SOTF) Logic

Upon energization, line voltage is zero requiring the phase and neutral overcurrent relay function to trip if a fault is present on the line as described in Case One. In addition to using voltage to determine whether the line is energized, the SOTF function for this circuit is also supervised by the line load current. When line current exceeds 4% of I nominal (i.e. 0.2 ampere secondary) and remains above that level for more than 200 ms, the SOTF is disabled, allowing the distance function to take over protection of the line. If a fault occurs after the line has been energized, a voltage level as low as 75% could be present. The SOTF logic would not react because of a 2 second time delay on the voltage reset. No output from this SOTF function would occur because the blockout feature associated with the line current is greater than 0.2 ampere secondary.

The first question was “Why did the protection of the faulted line 9 at Wild not operate?” The investigating team collected and reviewed relay targets, sequence of event and fault records captured by the line 6 and line 9 relays at Wild. Based on the reported relay targets and the captured fault records, it was found that the SOTF Trip element of the line 6 relay at Wild asserted on the line 9 fault. As a result, the breaker 6 tripped in 1.5 cycles, which is faster than the response time of the line 9 relay. This explains why Wild breaker 6 tripped and why Wild breaker 9 did not trip.

The next question was “Why did the SOTF function of the adjacent line 6 protection at Wild respond to the line 9 fault near Shill?” Refering to the SOTF logic shown above, the SOTF Trip asserts if the undervoltage supervision (27 Vpol) and phase or ground overcurrent fault detector (50Ia, 50Ib, 50Ic or 50-3I0) pick up and the pre-fault load current is less than 4% of I nominal, i.e. less than 0.2 ampere secondary. In this case, the line 6 fault detector sensed the fault current, which was higher than the pickup value, and correctly asserted. However, undervoltage supervision also picked up although the voltage detected by the relay was not lower than 75% of the nominal voltage. This led to reviewing the setting of the 27 Vpol. It was discovered that the 27 Vpol was set improperly at nominal voltage, so it is always asserted including at the moment of the line 9 fault. Up to this point, both fault detector and voltage supervision had picked up, so status of the SOTF Trip would depend on if the SOTF was enabled, i.e., if the pre-fault load current was greater than 0.2 ampere secondary. By further review of the DFR fault record at Wild, it was noticed the pre-fault current was 0.19 ampere secondary (see Figure 6 for the fault records), which explained why the current supervision inside the SOTF logic did not work as desired during this fault.

Two follow-up actions were taken based on the findings from the investigation. 1) A setting correction on the undervoltage supervision pickup, 27 Vpol, of the line 6 relay was implemented, and 2) Recommend the relay manufacturer using breaker position to supervise the SOTF enable logic.

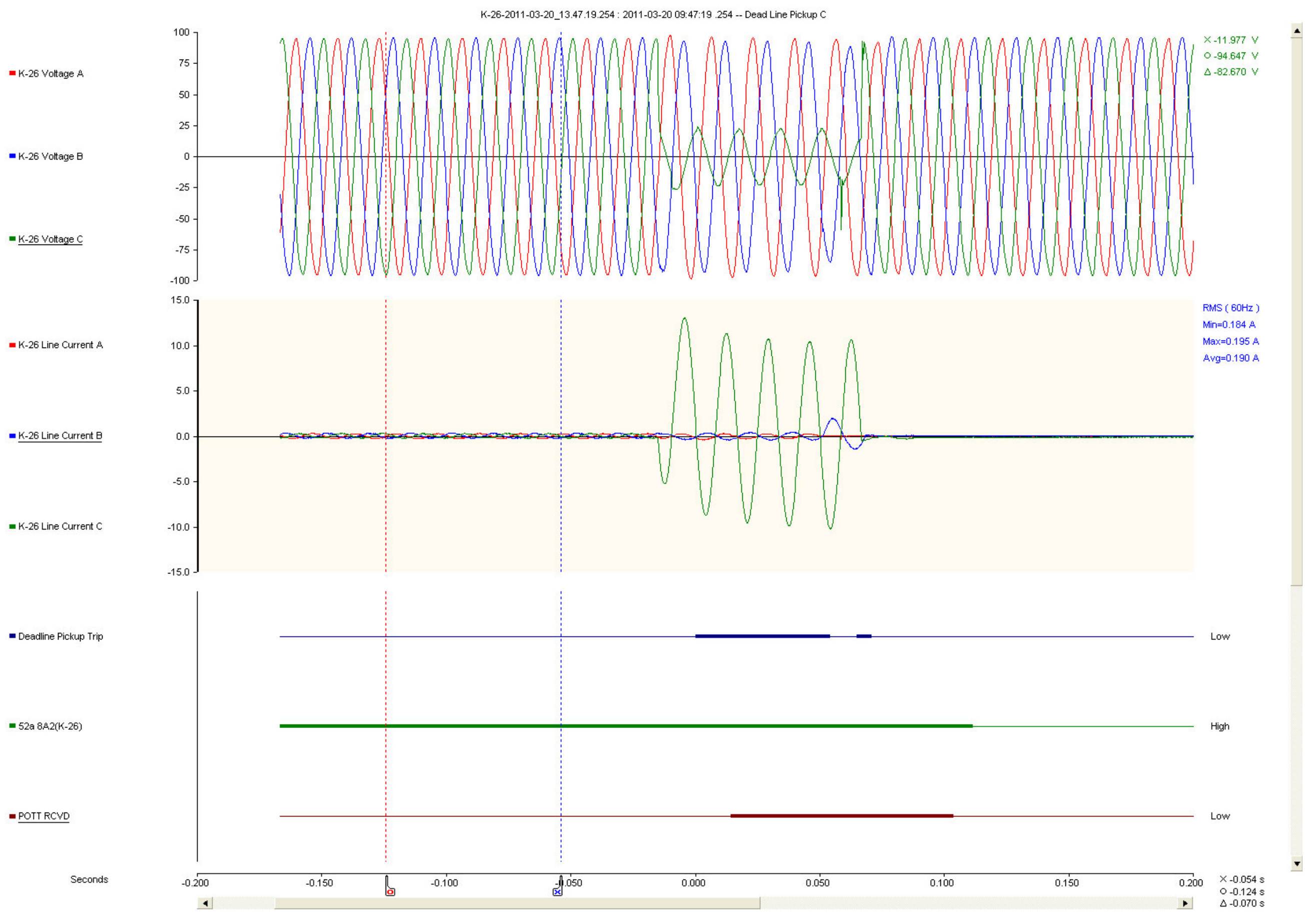


Figure 6. Line 6 Fault Record at Wild Substation on 03/20/2011

Case Three: Undesirable operation of SOTF element when energizing an 115kV cable from remote end

Referring to Figure 7, substations V & B are sourced from two 115kV lines M-165 and P-142S. Also, an 115kV underground cable B-180 runs between the two substations. At these substations, each source line supplies a transformer through individual circuit switchers 89-2. Cable B-180 is tied to the source lines through the normally closed in-line circuit breakers 8A1. Line side circuit switchers provide visible disconnection points. Voltage transformers (VT) for B-180 are provided at both substations.

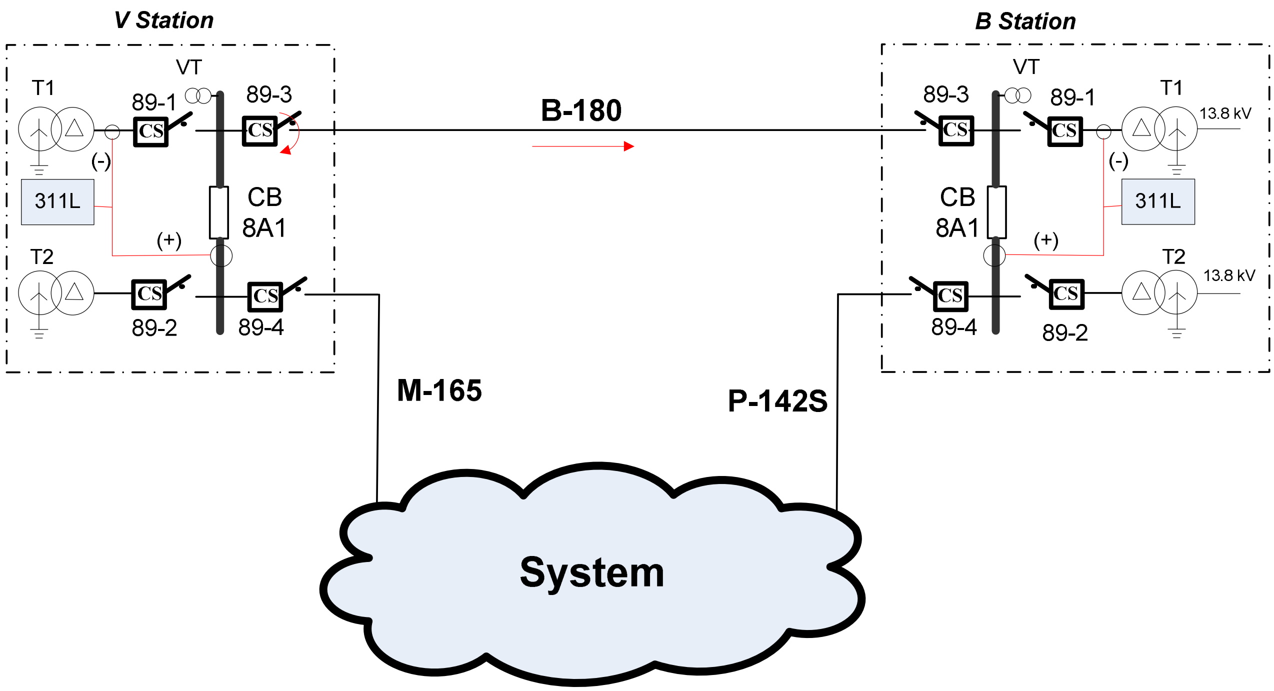


Figure 7. Simplified system diagram

Cable B-180 is protected with dual microprocessor-based systems at both B & V substations. A line current differential (LD) scheme provides high speed tripping for all B-180 cable faults (phase and ground) without intentional time delay. Each terminal senses current and compares it to the current at the other terminal via direct fiber communication. In addition to line current differential protection, the backup distance, directional, non-directional overcurrent and switch-onto-fault (SOTF) functions are included in the relays.

As described in Case One, SOTF function is provided to detect close-in-phase-faults upon energizing or reclosing into a line since there is no voltage present to provide a "memory" voltage to the distance elements. This protection is active for a short time after the 115kV in-line breaker is closed.

To obtain the "pure" line current for cable B-180 protections, the secondary current from in-line breaker bushing CTs is subtracted from HV side bushing CTs of tapped transformer. Once the protections of B-180 operate, both the 115kV in-line breakers 8A1 and circuit switchers 89-1 for tapped transformer at both B & V substations would be tripped.

On May 9th of 2012, SOTF protective function at B station unexpectedly operated when the de-energized B-180 cable and no load transformer T1 at station B were energized from station V by closing line switch 89-3. Prior to this energization, the status of breakers and circuit switchers at sub station B & V was shown below:

	Circuit Breaker 8A1	Circuit Switcher 89-1	Circuit Switcher 89-3	Circuit Switcher 89-4
Substation B	Open	Close	Close	Close
Substation V	Close	Close	Open	Close

When B-180 cable and transformer T1 at station B were energized, the current seen by line relay at substation V was the summation of B-180 cable charging current as well as transformer T1 inrush current. The current seen by line relay at substation B was only transformer T1 in-rush current because the in-line breaker 8A1 was open. The relay record from substation B is shown in Figure 8.

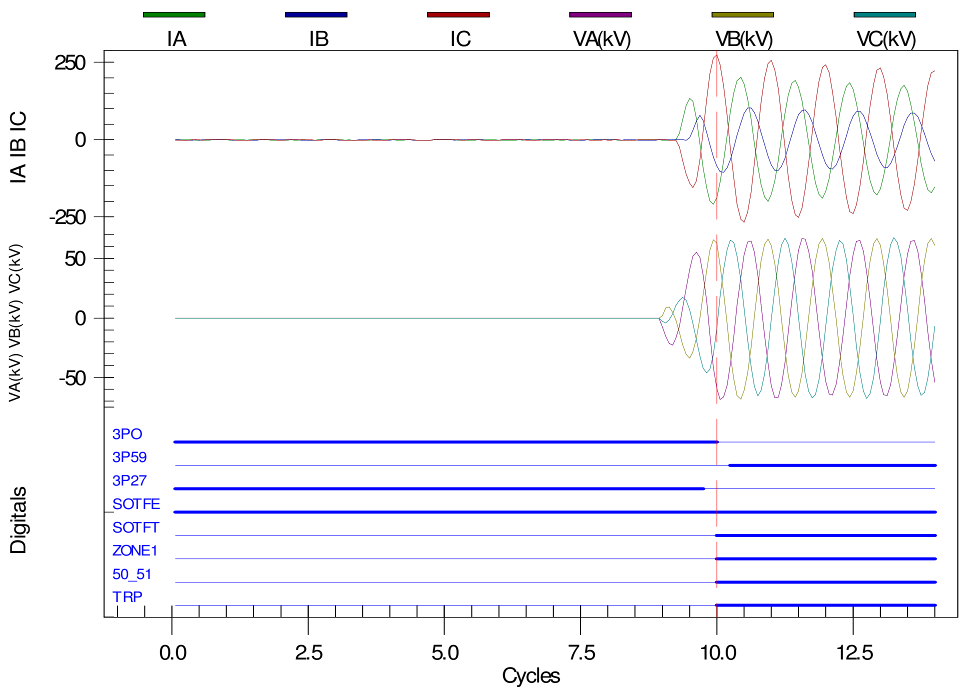


Figure 8. B-180 relay record from Station B

Per records from Station B, it can be seen:

- The transient inrush current during energization was 240 primary amps;
- Three pole open relay word (3PO) de-asserted in 0.75-cycle after presence of inrush current even though breaker 8A1 was still open;
- Three-phase under-voltage relay word (3P27), which is used for SOTF OC supervision, de-asserted in 1.2-cycle after B-180 energization;
- Switch onto fault enable (SOTFE) relay bit was on;
- SOTF current detector element 50_51 asserted in 0.75-cycle after presence of inrush current;
- The trip (TRP) was made after assertion of 50_51 element.

Why did the “3-pole open relay word (3PO)” de-assert while breaker remained open, causing the SOTF trip? Referring to Figure 9, the 3PO relay word is controlled by both breaker 52a auxiliary contacts as well as low current level indicator 50LP. When any of two conditions is breached, the relay would identify the close status of the breaker. The advantage of this kind of logic is that it guarantees the “true” breaker status if 52a contact fails. However, this logic is not suitable for this particular abnormal operational configuration. The delayed drop-out timer SOTFD provides a time window after the breaker is identified as not open (none 3PO).

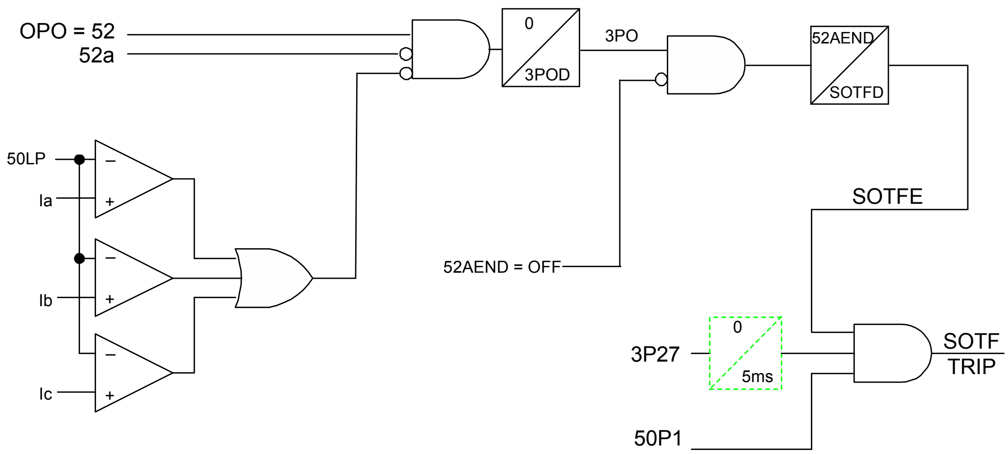


Figure 9. Switch Onto Fault logic

Per relay setting, 3-phase under-voltage supervisory element (3P27) was given 5 ms drop-out time delay and SOTF OC pickup setting was 200A which was even lower than maximum load of the cable (1963A). When transformer T1 at station B was energized from station V via cable B-180, the transformer inrush current (240A) exceeded the threshold of 50LP (50A) and SOTF OC (200A). After cable energization, the voltage started to build-up and under-voltage element quickly dropped-out. Due to delay of 3P27 drop-out timer, de-assertion of 3PO and assertion of SOTF current detector element 50_51, the switch onto fault logic was enabled and a trip command was then issued.

The unusually low pickup setting of the SOTF current detector was based on a special scenario: P-142s line is outage or line switch 89-4 is open and the dead cable B-180 will be energized from Station B by closing in-line breaker 8A2. Under this scenario, the 115kV stub bus on P142S side would be energized from the 13.8kV system via transformer T2 and the close-in fault current on B-180 would be only 520A, which is the backfeed from 13.8kV system.

After operation of the relay, it was confirmed with dispatch and transmission planning that the abnormal configuration originally of concern is unlikely to occur, i.e. 115kV cable B-180 will always be energized from 115kV system. Therefore the revised OC pickup value of SOTF function could be based on normal system configurations. In addition, the drop-out time delay (5ms) for under-voltage supervision (3P27) was removed, disarming the SOTF function once line voltage is well established and the line is being protected by the directional distance element.

If cable B-180 was energized from Substation B by closing the breaker 8A1, the transformer T1 inrush current would be subtracted from breaker bushing CTs. Then the only current seen by the line relay was cable charging current, which is approximately 30A, and this type of undesirable SOTF operation would be avoided.

Lessons learned:

The pickup value of SOTF fault detector should take into account the fault duty under abnormal system configurations. Otherwise, undesirable relay operation under abnormal operational configurations could occur.

Yujie Irene Lu 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. Irene has been employed in Protection Engineering at National Grid since 1990. She is a principal engineer in the Department of Protection Policy and Support, where she analyzes system disturbances, performs system analysis for short circuit conditions, develops/revises protection and control system standards and guidelines, designs protection systems on a conceptual basis, specifies equipment and determines protection settings and logics. She has 20 year's experiences as a lead protection engineer on projects and worked on installation of major 345/115kV GIS transmission substations. Irene has represented the National Grid as a standing member of NPCC TFSP (Task Force on System Protection) and SP-7 (System Protection Misoperation Review working group) since 2011. Previously, Irene worked for the Department of Energy of China for 5 years. 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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