Analysis of the Nuisance Tripping of a Dead Line Adjacent to a Faulted Line

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Introduction

A well-established objective for power system protective relaying systems is the removal faults while tripping only as much of the power system as is necessary to interrupt the fault current. Achieving this objective enhances the stability of the power system and maximizes continuous load service, whereas nuisance tripping of power system elements contributes to a weakened system and unnecessary load interruption. This paper examines a nuisance tripping event whereby a transmission line adjacent to the faulted line tripped along with the faulted line despite the unfaulted line having been previously isolated from the power system. The analysis will show that nuisance trip resulted from of a combination of instrumentation and operations issues.

System Overview and Incident Summary

F-Square Sub is a 115kV station with a breaker-and-a-half bus configuration connecting a number of transmission lines. The R-144 and Q-143 lines are both 115kV 3-phase underground cables, each normally serving a 23kV subtransmission system through delta-grounded zigzag transformers at A-Street Sub. The SS-T1 line is an overhead line which serves 11.5kV distribution load at S-Street Sub through a wye-wye transformer. The Q-143 and SS-T1 lines share the same bay position at F-Square Sub. The 1-line diagram in *Figure 1* illustrates this arrangement.

Before the R-144 fault event, the Q-143 line was in a contingency arrangement (out of service and isolated by open disconnects at each end) because of a previous Q-143 cable fault. This contingency arrangement had been in place for roughly 2 years pending repair of the Q-143 cable. With the Q-143 cable isolated, the corresponding F-Square Sub breakers (43-20 and Q143-1T) were closed to provide normal service for the SS-T1 line. The 1-line diagram in *Figure 1* illustrates these contingency arrangement details as well.

On August 25, 2016 a fault B-phase single-line-to-ground (SLG) fault occurred in the R-144 cable. Both systems of R-144 line protections operated correctly, tripping associated breakers at both the F-Square (43-30 and R-144) and A-Street subs. At the same time Q-143 and SS-T1 line System 1 protections operated incorrectly, tripping associated breakers at both the F-Square (43-20 and Q143-1T) and A-Street subs. Neither of the Q-143 or SS-T1 line System 2 protections misoperated. The 1-line diagram in *Figure 1* illustrates these fault and breaker tripping details along with observed fault currents. *Figure 2* provides the reported target information for the protection elements which operated.

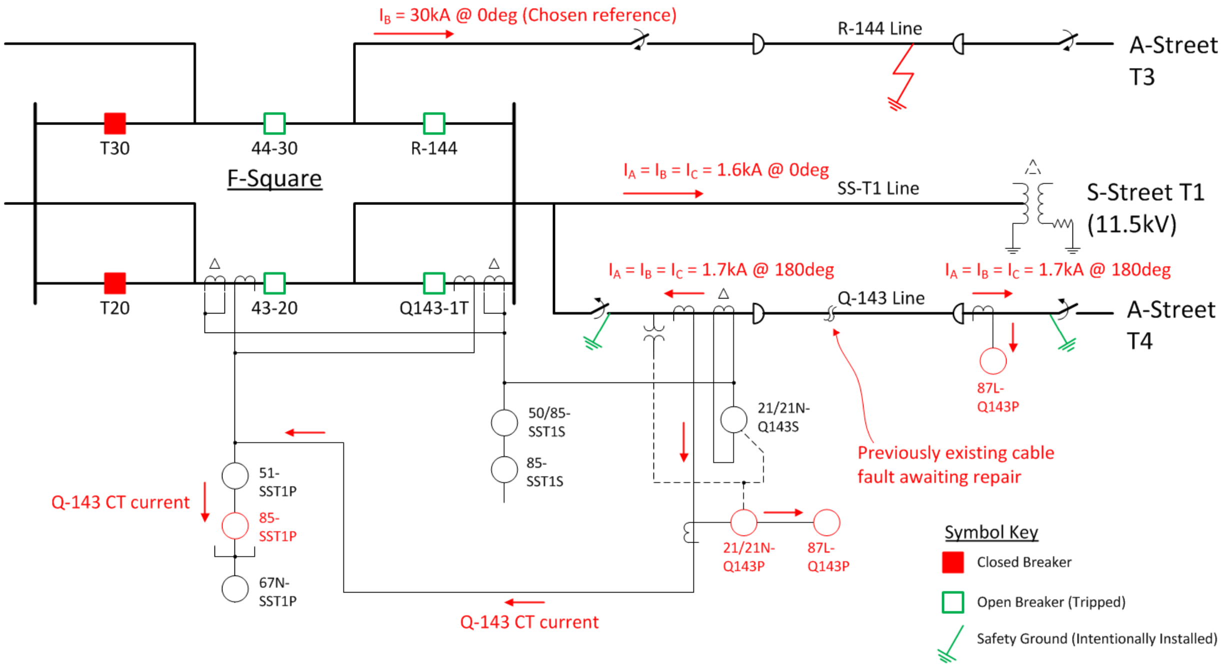

Figure 1: Area 1-Line Diagram Illustrating Operating and Fault Conditions

Investigation and Analysis

Correct operation of the R-144 line protections was both expected and observed. While the SS-T1 line misoperation certainly prompt analysis, the Q-143 line System 1 protection misoperation was especially curious. With the Q-143 line having been previously deenergized and physically isolated from the power system, how could it possibly be involved in the R-144 line fault? Over the previous 2 years there were other R-144 line faults, none of which invoked misoperation of the Q-143 or SS-T1 lines. How did this event differ?

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F-Square:  R-144   System 1:  87L (BG), 21N-1 (BG), 50N (BG), Distance = 1.5mi
           R-144   System 2:  21N-1 (BG), 50N (BG), Distance = 1.8mi
           Q-143   System 1:  87L-Q143P (ABC), 21P-1 (ABC), 21N-1 (AG), Distance = -2.6mi
           SS-TR1  System 1:  85-SST1P (Pilot Wire)

A-Street:  R-144   System 1:  87L (BG), 59N (Ground Overvoltage)
           Q-143   System 1:  87L-Q143P (ABC)
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Figure 2: Reported Relay Targets for F-Square and A-Street Subs

R-144 Line Operation – Correct Operation

The target information from *Figure 2* indicates that both systems of protection operated. That was to be expected since the design intent of both systems provides for similar fault sensitivity and timing characteristics for each. F-Square Sub System 1 protection targets include a line differential function (87L) which reported B-phase as being the faulted phase. F-Square Sub Systems 1 & 2 targets both included 21N-1 and 50N assertions also reporting B-phase as the faulted phase and with similar fault distances.

A-Street Sub targets included the line differential (87L) companion to the F-Square differential target as well as a ground overvoltage (59N) target. The latter was likely due to the elevated voltages on the unfaulted (A and C) phases.

A review of the R-144 line voltages and currents in *Figure 3* (top 2 graphs) shows the cable fault to be a B-phase SLG fault (approximately 32.8kA) which was cleared in about 3 cycles. The A-phase voltage signal shows signs of clipping, which is consistent with the observed 59N relay target reported at A-Street.

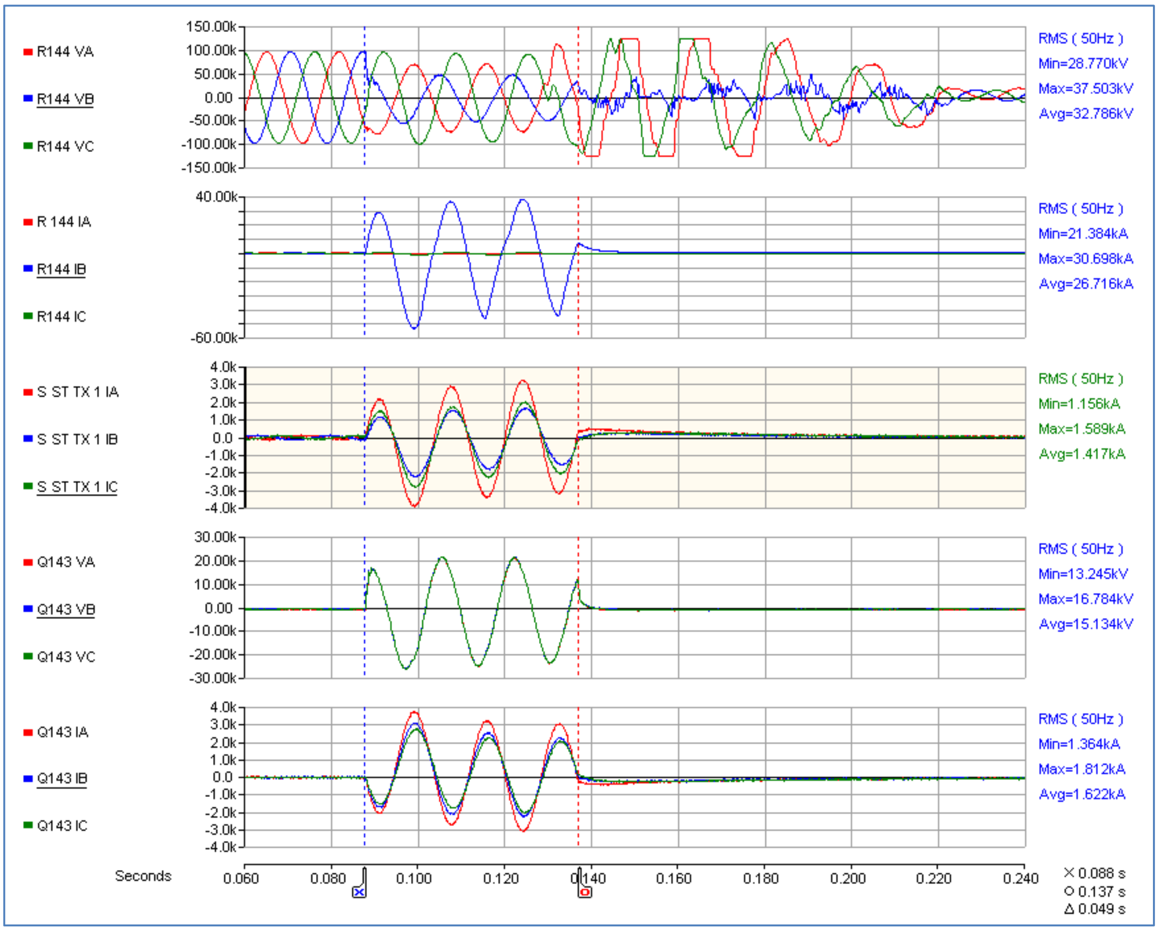

Figure 3: F-Square Sub DFR Waveform Data for the R-144, Q-143 and SS-T1 Lines

The fault current traces in *Figure 4* from the F-Square Sub R-144 line differential relay provide additional supporting details. The set of local end currents (*IAL, IBL, ICL*) are a classic SLG fault signature. The remote end currents (*IAX, IBX, ICX*) illustrate weak infeed from the 23kV subtransmission system appearing as a phase-to-phase fault because of the A-Street step-down transformer's delta-wye winding arrangement. Fault clearing from the A-Street side is also slower (beyond the record limit) because tripping is via 23kV breakers. Also shown in *Figure 4* are phasor comparisons of local and remote currents both before and during the fault, illustrating the differential relay's Alpha-plane performance during both timer periods. Although an Alpha-plane plot couldn't be generated from the relay data using the vendor's software, the phasor comparisons show the pre-fault IL/IX ratios plot inside the restrain region whereas the fault IL/IX ratios plot well outside the restrain region.

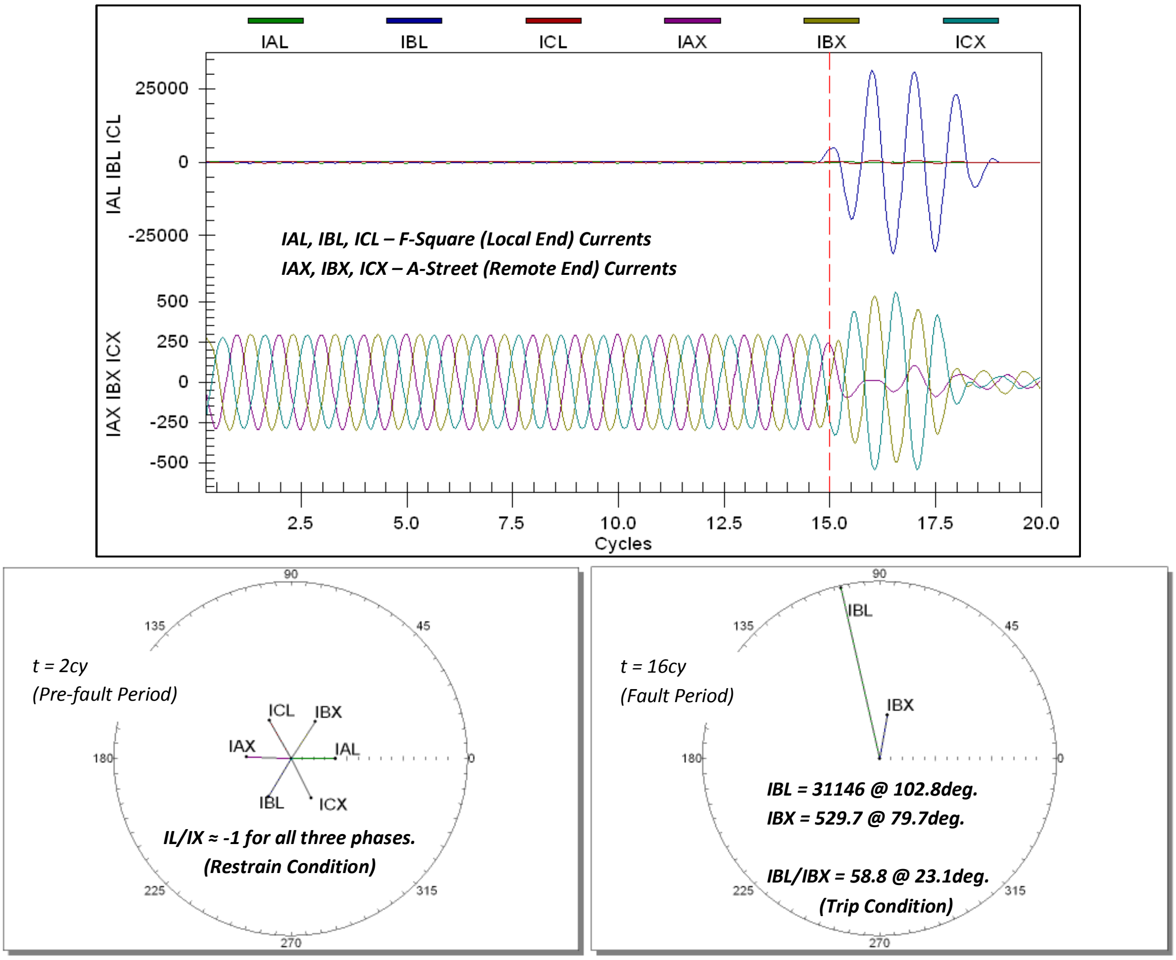

Figure 4: F-Square Sub R-144 Line Multifunction Differential Relay Fault Data

Overall, this part of the event was unremarkably a correct operation.

Q-143 Line Misoperation

The waveform data for the Q-143 line in *Figure 3* is a stark contrast to that for the R-144 line. That there was any fault current at all on this line is unexpected. That the fault current is entirely zero sequence current (i.e. I_A, I_B and I_C are all predominantly of similar magnitude and are all in phase) is doubly odd. The sequence composition of the Q-143 line current clearly indicates that it did not originate from a balanced 3-phase source. Since the line consists entirely of an underground cable, the current also did not originate from any mutual coupling. Since the cable was isolated from the power system by open disconnects at both ends, how could current of any kind have flowed at all?

It was postulated that safety grounds had been recently added to the ends of the cable. This conjecture was verified with field operations personnel who confirmed that safety grounds had, indeed, been installed literally the week before this event in preparation of a repair project. The safety grounds effectively transformed this 3-phase cable into a multi-conductor neutral. The observed current was simply a portion of the earth return current from the R-144 line fault. That the safety grounds were a recent addition is also consistent with there not having been any previous misoperations of the Q-143 line protections for R-144 line faults.

With this discovery, the task is now to determine if this arrangement supports observed measurements and protection responses and if this outcome could be arrived at analytically. Target information from *Figure 2* indicates that the following protection functions asserted to produce a trip at F-Square Sub: 87L-Q143P (ABC), 21P-1-Q143P (ABC), 21N-1-Q143P (AG), Distance = -2.6mi. *Figure 2* also indicates that the following protection functions asserted to produce a trip at A-Street Sub: 87L-Q143P (ABC). These targets are also highlighted on the 1-line diagram in *Figure 1*.

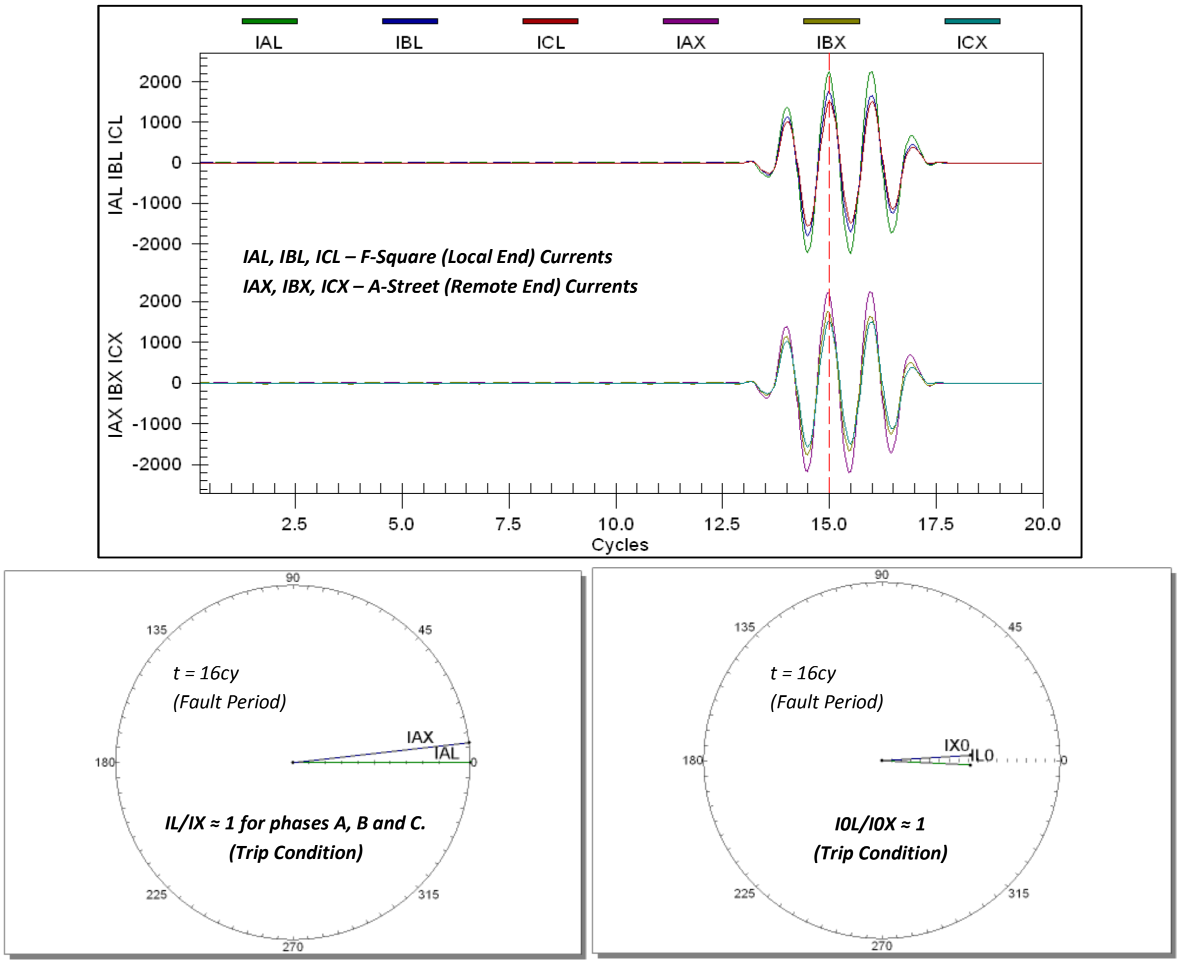

Figure 5: F-Square Sub Q-143 Line System 1 Multifunction Differential Relay Fault Data

Starting with the System 1 differential (87L) protections, the waveform record in *Figure 5* indicates that all zero sequence current exited the cable through CTs at both ends (i.e. IL currents were in phase with IX currents). The Alpha-plane response IL/IX evaluates to IL/IX ≥ 0 for A, B and C phases as well as I0, which is a trip state and is consistent with the observed targets. Normally, local and remote line currents being in phase indicates current entering the cable at both ends because of an internal fault. However, a comparison of F-Square Sub Q-143 line and R-144 line B-phase currents (Refer to *Figure 3*) suggests that Q-143 line current is flowing from the cable towards F-Square Sub on that side and consequently from the cable towards A-Street Sub at the remote end. How is this possible? One possible explanation is that the damage point on the Q-143 cable provides a ground point between the safety grounds, which then splits the return current. Another possibility is the presence of an additional safety ground at one or both of the cable terminations. Unfortunately a positive determination could not be made for either conjecture. Even so, the observed line currents and 87L relay behavior is consistent with the addition of safety grounds.

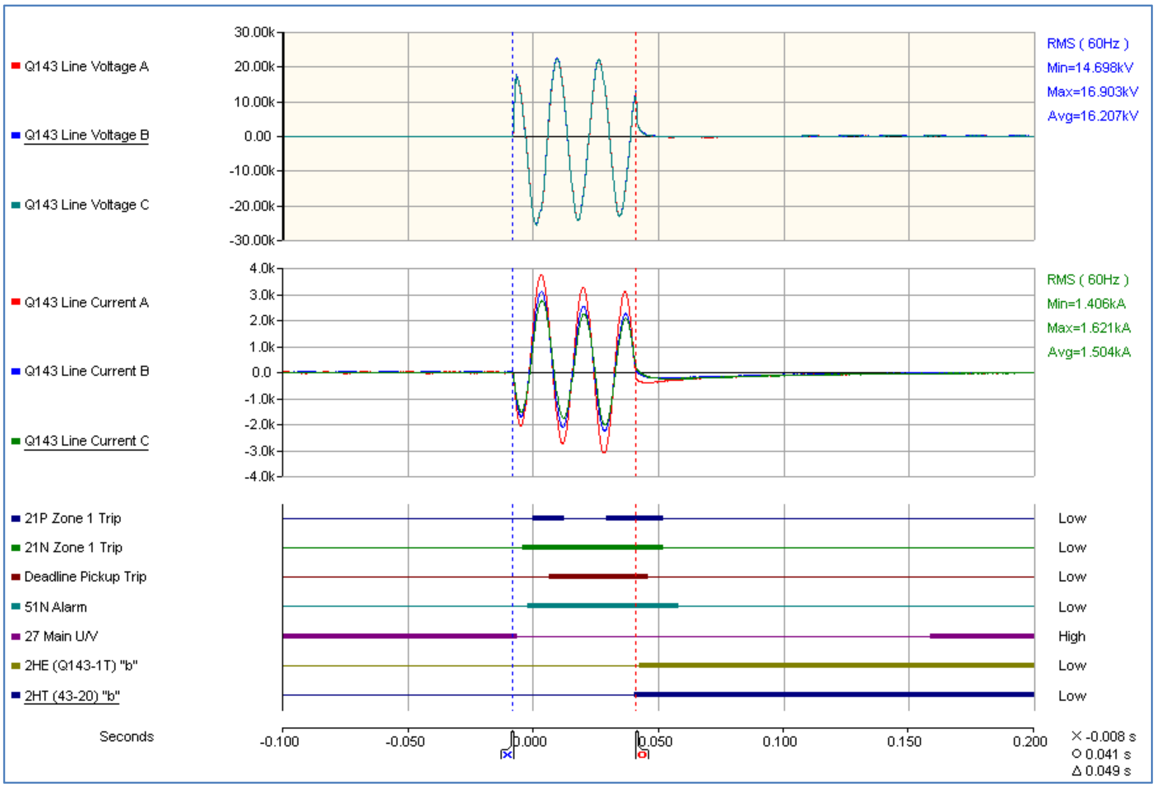

Figure 6: F-Square Sub Q-143 Line System 1 Multifunction Distance Relay Fault Data

The distance relay behavior is less straightforward. F-Square System 1 distance (21/21N-Q143P) protections operated whereas System 2 distance (21/21N-Q143S) protections did not. Nonoperation of the System 2 relay is explained by the observation that it is fed by delta configured CTs; which block the flow of zero sequence current to the relay. For the System 1 relay, *Figure 6* shows the apparent impedances as plotting behind the relay. This is consistent with the reported distance-to-fault being negative. It is also consistent with the current direction inferred from the 87L relay data. Note that the measured voltages are simply the voltage drops on each phase between the CTs and the safety ground behind them produced by the measured all-zero-sequence line current. Effectively, the apparent impedances represent the line impedances between the relay location and the safety ground behind it.

A comparison of the impedance trajectories with the 21/21N-1 reach settings in *Figure 7* show that the apparent impedances for phases A and C plot well within the Zone 1 characteristic. Depending on the dynamic characteristic of the B-Phase B it is likely that the B-Phase impedance trajectory passed through the Zone 1 characteristic long enough for it to have asserted since a B-Phase target was also reported. This misoperation is simply a consequence of the CTs and VTs having been located inside the open disconnects. While the cable was isolated from the power system, the instrument transformers were still sending active voltages and currents to the relays. From this analysis, the observed 21/21N-Q143P relay behavior seems consistent with the addition of safety grounds.

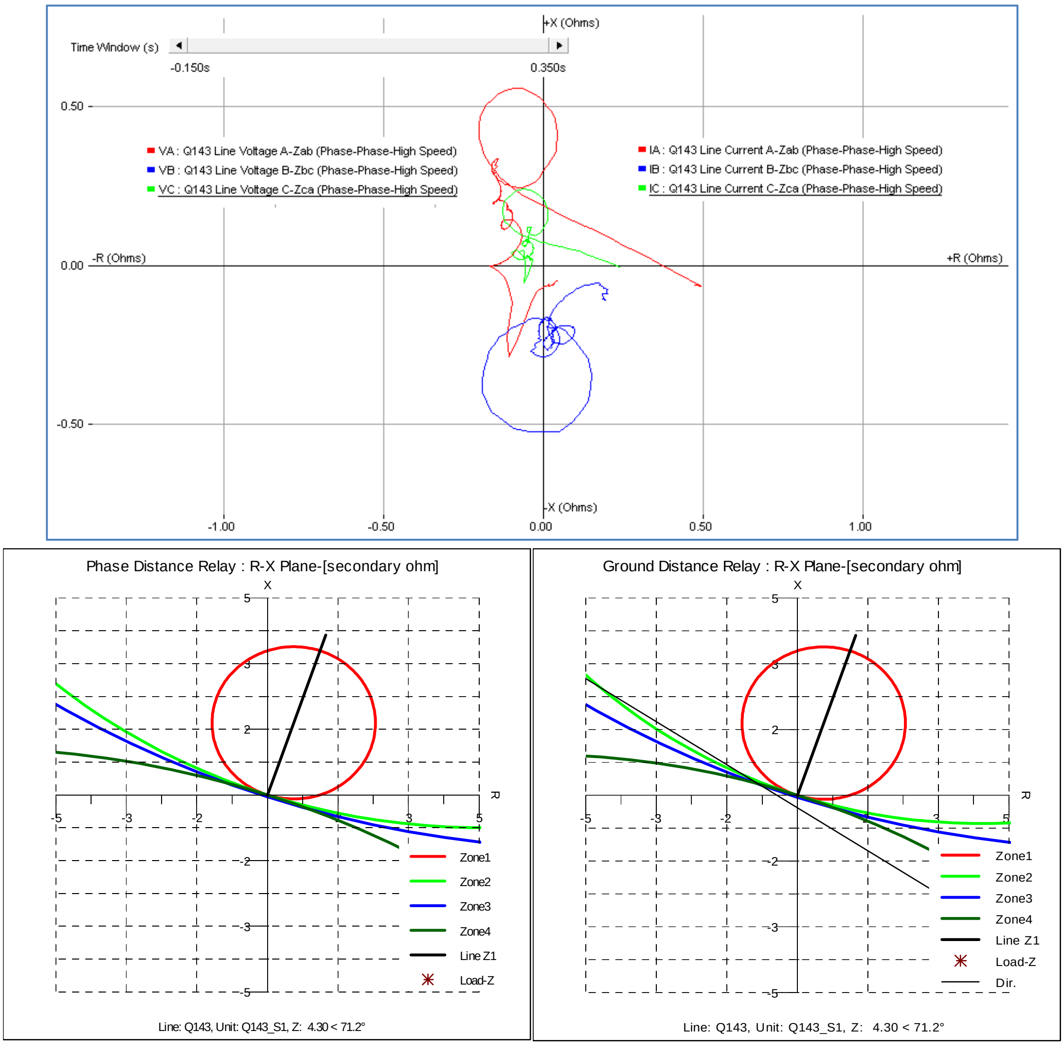

Figure 7: Comparison of F-Square Sub Q-143 Line Apparent Impedance Trajectories With Q-143 Line System 1 Relay Distance Element Setting Characteristics

SS-T1 Line Misoperation

SS-T1 line currents in *Figure 3* (3rd graph) are entirely zero sequence current like Q-143 line currents (bottom graph). The direction of Q-143 line current is from F-Square Sub towards the S-Street Sub.

How does this all-zero-sequence current flowing on the deenergized and isolated Q-143 cable manage to find its way to flowing also on the SS-T1 line? It cannot and it does not.

The odd currents observed on the SS-T1 line are a consequence of poor Q-143 cable CT placement. The currents measured by Q-143 line CTs do not properly represent primary side currents. The false Q-143 line CT currents combine with 43-20 and Q143-1T breaker CT currents to form false SS-T1 line currents. *Figure 1* illustrates the flow of CT secondary currents. The prefault SS-T1 line current magnitudes in *Figure 3* are around 100A per phase whereas the current magnitudes during the fault are roughly equivalent to the measured Q-143 line current magnitudes (approximately 1200A per phase). It is clear that the measured SS-T1 line fault currents; which resulted in the misoperation of the SS-T1 pilot wire (85-SST1P) relay at F-Square Sub, were simply the product of bad instrumentation.

Conclusions and Lessons Learned

Out of this experience and subsequent analysis came two important conclusions.

Bad Instrument Transformer Placement

The CTs being on the inside of the Q-143 cable disconnects is problematic. While the Q-143 cable was isolated, the CTs and VTs were not. Consequently, they produced a false measurement. The better location would have been for CTs and VTs to be installed on the bus side of the F-Square Sub cable disconnects. Had the instrument transformers been so placed, then they would not have combined partial ground return currents with breaker currents to produce meaningless measurements on which relays would make trip decisions. Why the instrument transformer arrangement was as it was is largely a historical progression. The R-144 cable was originally equipped with condenser potential devices (i.e. combination VT and CT) built into the cable termination. These devices were a solution to a space availability problem. Since relocating the instrument transformers is likely impractical, it becomes necessary to identify and understand any operational limitations the current arrangement imposes.

It was determined that this same CT/VT arrangement exists on the R-144 line at F-Square Sub so what is learned for the Q-143 line is applicable to both lines.

Inadequate Awareness of Operational Constraints Imposed by CT/VT Placement

While the placement of CTs and VTs on the Q-143 cable is problematic, a better awareness of necessary operational constraints that such placement imposes translates to a need for operating procedures for adapting protections to for outage of either of these cables. Shorting the Q-143 cable CTs in tandem with safety ground installation would have prevented both the Q-143 and SS-T1 line protection misoperations by removing the source of erroneous current injection. Since the two activities (switching and protection maintenance) are done by different groups, it becomes necessary for construction and maintenance procedures to coordinate these groups and activities.

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<u>Dean Sorensen</u> received a B.S. degree with distinction in Electrical Engineering in 1984 and an M.S. degree in Power Systems Management in 2002 both from Worcester Polytechnic Institute (WPI). He is a member of IEEE and is a registered professional engineer in the state of Massachusetts. Dean has over 30 years of experience in the power industry serving in various engineering capacities in transmission, distribution and generation primarily in the areas of protection and controls and power quality. Dean is a principal engineer in the Department of Protection Policy and Support at National Grid. Dean has also been on the faculty of WPI since 2011 as an adjunct instructor teaching graduate courses related to power system protection.