Relay Mis-operation caused by Arcing CT and its Mitigation Discussions

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Presented at the
Georgia Tech Fault and Disturbance Analysis Conference, May 6. 2013

Abstract

This paper examines a bus differential relay mis-operation that was caused by an arcing CT. The tripping of the relay was defeated and portable fault recorders were installed during the investigation period after the event. Waveform files from the fault recorders and data from the relay as well as the weather conditions were gathered and thoroughly analyzed. Preliminary results show the CT current of a transmission line and the voltage measured by the bus differential relay during the mis-operation match the arcing V-I characteristic very well. The fault recorder waveform data collected after the event also corroborate that the CT issue was the root cause as noisier measurements and wave distortion of the phase B CT were observed, especially during morning hours and rainy days when the moisture level was high. Possible relay protection modifications to mitigate the mis-operation of an arcing CT are also discussed.

Introduction

On June 12th, 2012, a bus differential relay (SEL-587-Z) in one of the transmission and distribution mixed GIS substations in Dominion Virginia Power (DVP) operated. It tripped two local GIS breakers (BKR3 and BKR4 in Figure 1) and transfer tripped two line breakers at the other end of the affected transmission line (Line3 in Figure 1), locking out the line and causing power outage for more than 50,000 customers. The bus differential relay under investigation is set up to protect the green section of the GIS system in DVP shown in Figure 1. This is a 230 kV GIS substation and there are 6 overhead transmission lines and a 230/34.5 distribution transformer connected to the GIS system via gas to air bushings. CT1 through CT4 are summed up to provide input to a high impedance bus differential relay SEL-587Z.

There was no fault on the bus and this event is clearly a mis-operation with great reliability impact. Although, this relay mis-operation and the subsequently transmission line lockout created no stability issues on the DVP transmission grid, thorough inspection, testing, investigation and study have been conducted to find the root cause of this event due to its high reliability impact and its rarity of occurrence. The process had gone on for almost a year and the bus differential protection scheme was defeated until confidence was gained that problem was solved. On April 30th, 2012, the differential relay was placed back into service, ultimately completing the investigation and the corrective action plan.

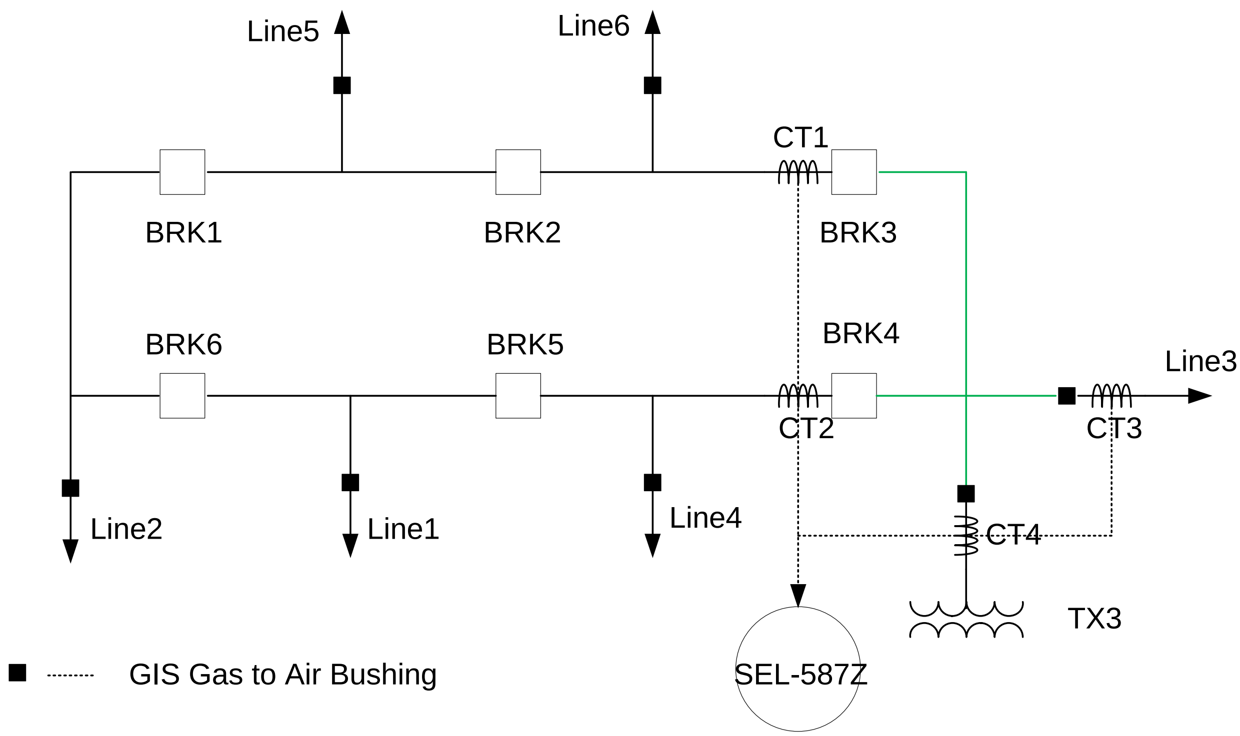

Figure 1

Investigation Process

The bus differential relay removed from the field was sent back to the DVP's relay lab and underwent diagnostic testing with the field COMTRADE files to try to understand the waveform and the relay's reaction right after the event. No problems were found, however, in the returned SEL-587Z.

A portable digital fault recorder (DFR) was installed to monitor all the separate current inputs to the bus differential scheme. Clip on CTs were placed around the secondary CT circuits. The differential relay was set to a low trip value of 20 volts and its tripping functionality was defeated. An output of the relay was wired to trigger the fault recorder whenever the trip setting was reached.

Fault recorder records showed noisy measurements on B phase CT circuits that started minutes before the trip and were also present on several occasions a few days after.

On site testing after the outage with the gas bus differential relay lockout blades pulled revealed that the B phase CT on Line 3 was producing a sporadic differential current as demonstrated in Figure 2.

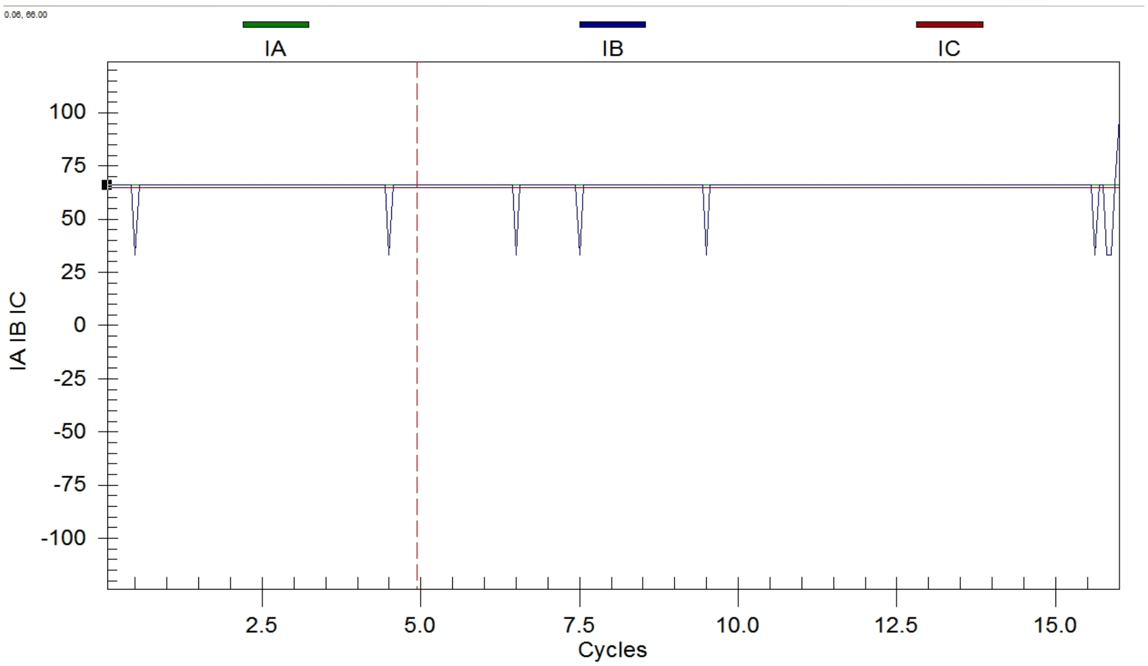

Figure 2

The waveforms that the portable DFR captured the next day after it was installed, which was nearly a month after the event, still showed the problem with the B phase CT, as seen in Figure 3. All evidence from the extensive monitoring and testing that were conducted pointed to a problem with the Line 3 B phase CT.

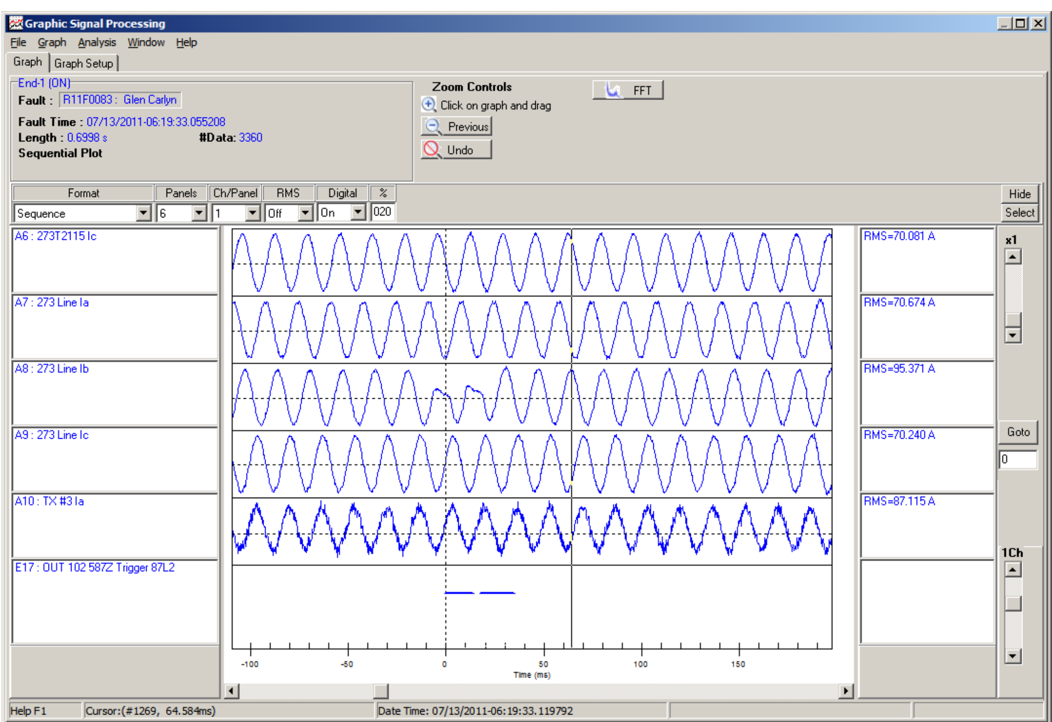

Figure 3

Almost 3 months after the mis-operation, the DFR was still triggering regularly, most often in the early morning hours. Figure 4 shows the traces of an event triggered by the bus differential trip signal. We didn't see any examples of the waveform being cut off like we saw at first; at this point it seemed that most of the records were just "wavering" currents produced by the line 3 B phase CT.

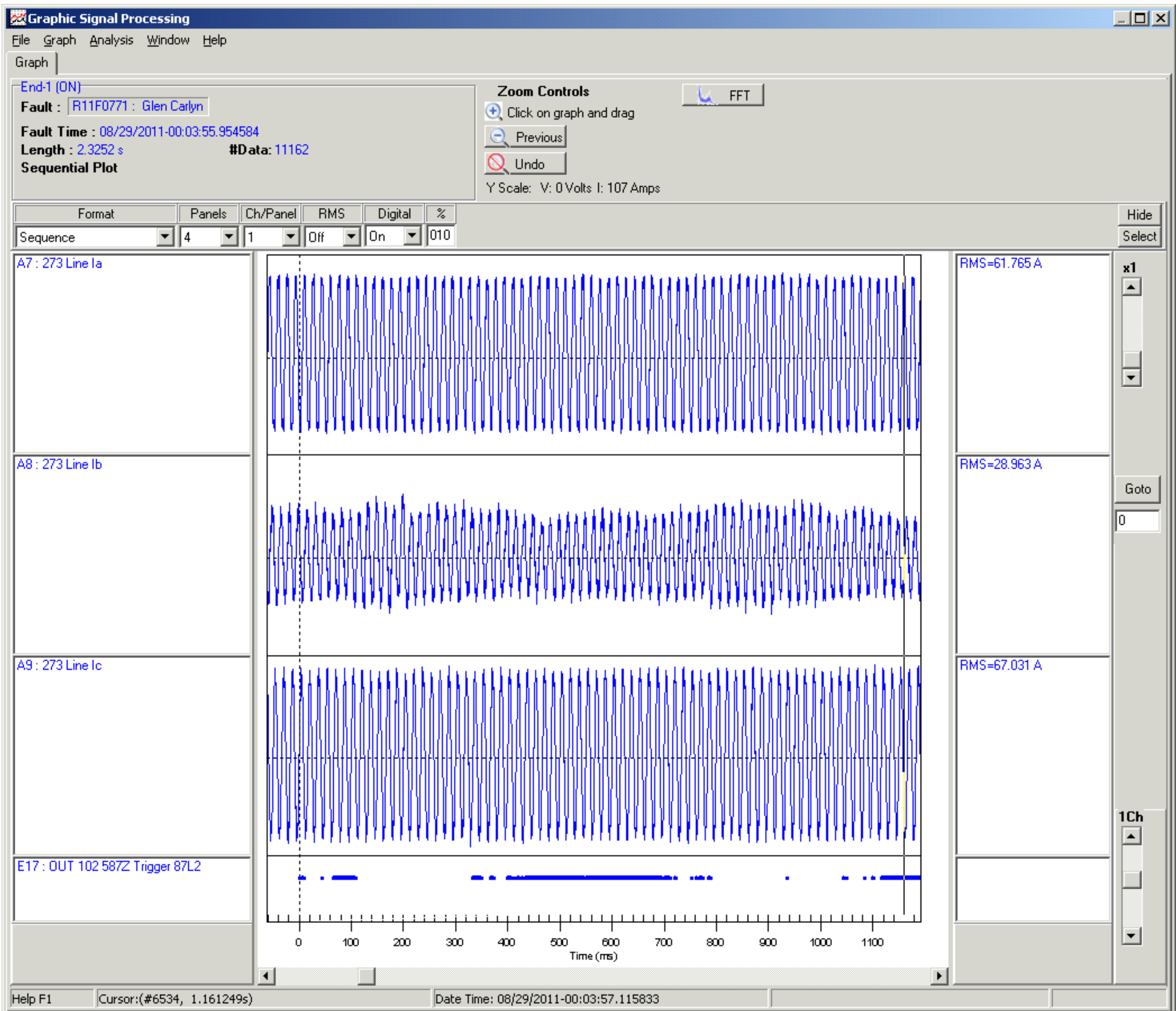

Figure 4

In the early phase of the investigation, it was noticed during a close physical inspection that the clearance between the bushing CT shield and the gas-to-air entrance bushing was nearly zero. The CT was not centered around the conductor properly. It was first believed that the CT was actually touching, creating a magnetic shunt affecting the output of that CT that may have caused enough differential current to operate the relay. This was later ruled out as the cause because nylon bolts were installed on the CT shield as the first troubleshooting step. It turned out that the nylon bolts did not help and the relay was still tripping and shunting current, and the DFR continued to see activity from the erratic B phase currents and also from the output of the 587Z relay.

Originally, work was scheduled to center the CT on the bushing to correct the clearance issue, however the manufacturer agreed to replace the CT under warranty. The CT was replaced on February 14, 2012. Monitoring continued with the tripping defeated for several months until we were certain that problem was resolved. The bus differential relay last made an event two days before the CT was replaced. The other DFR also had a corresponding trigger on the same day that matched the time of the event on the relay. The portable DFR installed was left there for a few more months after the CT replacement to continue monitoring the CT. A recheck for events revealed no operations on the DFR and decision was made to disconnect the portable and confirm it was the CT internal problem that caused the mis-operation.

Fault Recorder Data Analysis and Factory Inspection Verification

The high-impedance elements SEL-587Z provides is a technology to convert bus differential current into voltage with a high-impedance resistor to achieve high sensitivity. The set point is usually around 100~300 volts after considering the CTs' knee point and the security for a saturated CT for through faults. As a free add-on feature, like every digital relay, the SEL-587Z can record event oscillography at a decent resolution when it is triggered by a predefined event.

During one event, the nearby DFR triggered many times in a two minute window of the mis-operation. The relay records show the same thing as the trip event - a lot of erratic B phase voltages on 87B measurements. The 87A and 87C phase elements did not show any differential voltages.

Strangely enough, the relay did not make an event report for the trip event. The relay trip actually occurred about 100 to 200 milliseconds after the last event report ended.
It is possible that the relay is busy protecting and making records (it made 10 events in 7 seconds), that its processor was a bit overloaded and did not record everything.

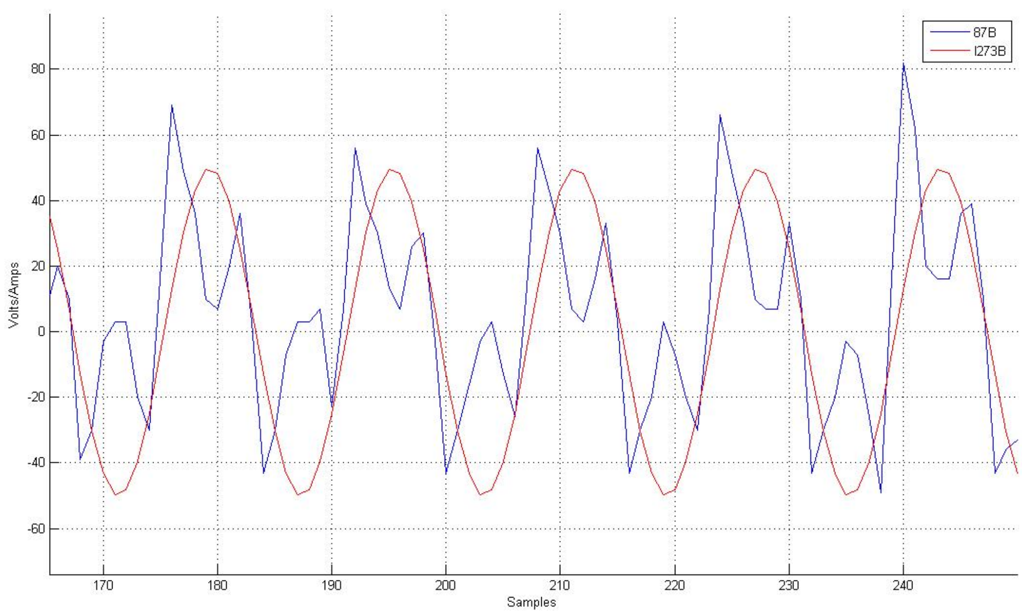

Figure 5

Although the exact voltage and current measurements on the SEL-587Z phase B bus differential element was not recorded, it was precise enough to trend phase B current on line 3 back to the time of the last event file the relay saved (about 0.2 second back) since the magnitude of the current did not change much and the system frequency was fairly close to 60 Hz. The maximum error on phase angle is only 0.5 degree even if the system frequency deviated 10 mHz from the nominal frequency.

After overlaying the current trended back from the DFR file on top of the voltage recorded on B phase bus differential element of line 3, we find the saddle-shaped V-I characteristics in Figure 5 are exactly what we expect for arcing[1]. When the current goes to zero, the voltage decreases to zero. When the current goes up to a certain point, it starts arcing and the voltage starts to drop. When the current goes to maximum, the arcing intensifies and the resistance of the arc decreases. As a result, the voltage drops to minimum.

This is the end of the relay event data. The fundamental voltage is over 30 volts RMS with the peak reaching over 80 volts. We can also notice that the arc voltage starts to pick up. It is very likely the arc voltage rose to 91 amps and tripped the relay whose 87B set point was 88 volts.

It is worth mentioning that the 88 volts set point for 87B was on the low side of the normal setting range. After checking with the circuit calculation group, it was realized the set point was supposed to be 292 volts. However the event files from the relay and the set point on the relay shipped back to the relay testing lab show the set point around the trip time for 87B was 88 volts on that relay and in the event files. It was then identified that the bus differential settings on the relay under investigation were for a different relay and were accidentally downloaded to the relay under investigation. The set point was set to 292 volts when a new relay was installed. If the relay had used the right set point, it would probably not have tripped for the reason that it is very difficult for the arc voltage to reach 292 volts. However, the possibility that a high impedance bus differential relay with the right setting file has a mis-operation like described above still exists since 88 volts is within the normal setting range.

Although there was arcing going on and the arcing was generating arc voltage, the CT currents could still flow as normal. This is why we did not see any differential current flowing through B phase while we see voltage on 87B.

The removed CT was sent back to the manufacturer for testing and analysis. It was later reported that there was an internal connection problem inside the CT that can cause arcing on the secondary side of the CTs.

The CT had a high resistance between the X4 and X5 taps. This high resistance was not the normal reading. An internal issue was found with the secondary leads as they were being prepared for the molding process. The quality of the brazing, combined with the twists the secondary leads took when they were being prepared for molding was believed to be the root cause for this failure. After all that, the lead for that part of the secondary winding was barely touching the rest of the winding. Enough was touching so that we could still perform routine tests, but not enough to show correct resistance readings.

The factory feels it was an internal problem caused by the brazing/molding process which damaged and compromised the wire connectivity between X4 -X5 tap.

The connection between the secondary winding and X5 was poor and thus causing an abnormal high temperature in that area. So, during a rainy & windy day the CT, in the area where the X5 terminal is located, was experiencing thermal shock and thus causing the high internal mechanical stresses around this terminal and as of a result changing the continuity between X1-X5 terminals.

The factory discussed these problems with the floor personnel and what they need to be aware of in the future when assembling CTs.

Conclusions

A bus differential relay (SEL-587-Z) in a DVP GIS substation had a mis-operation that tripped 2 local GIS breakers and transfer tripped two line breakers at the next substation, locking out the transmission line. There was no fault that could be identified. Post-mortem analyses using voltage and current recorded by the relay and the digital fault recorder show strong V-I characteristics of arcing. Field testing also ruled out other possibilities. The portable DFR records clearly indicated a problem with one particular CT and the root cause was found to be the B phase CT in one of the gas to air bushings. The CT was replaced under warranty. Furthermore, the manufacturer of the CT found an internal failure on a connection to the CT winding that was caused by improper assembly at the factory. The manufacture stated that this defect was an isolated case, not likely to be a recurring manufacturing defect.

The processes that can mitigate this mis-operation possibility from the discussions above include:

1) The lower the SEL-587Z bus differential voltage setting, the lower the possibility that the relay has a mis-operation due to a bad connection and possibly arcing at the secondary winding of a CT. The set point should be at least 100 volts to avoid this type of mis-operation.

2) One test in the CT plant that caught this was a resistance test which can be easily completed by the bridged ohmmeter in a substation. In the commissioning of a bus differential relay or during a mis-operation diagnosis, this bridged ohmmeter testing can help identify the CT connection issue and mitigate the relay mis-operation possibility.

About the authors

Dr. Tao Xia also has worked in Operations Engineering support at Dominion Electric Transmission since 2010. His job responsibility includes transmission operational event root cause analysis and transmission assets online monitoring, etc. He is also an expert in wide-area measurement system. He has nearly 10 years research experience on GPS synchronized power grid monitoring system.

Robert Orndorff has worked at Dominion since 1984. He spent 11 years as a field relay technician and in 1997 transferred to the Fault Analysis department where he now works. His current responsibilities include maintaining and configuring Dominion's Digital fault recorders, event retrieval and analysis from smart relays and DFRs. Robert is an IEEE member and has been a member of the Transient Recorder's User Council (TRUC) since 2002.

References

[1] Xipu Fan, Electrical Equipment in Power Plants (Chinese), Page 132,1995