Analysis of a Transformer Neutral Resistor Damage on an 11kV Bus Fault at National Grid

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Introduction

Power outage minimization and correct and rapid fault isolation are of concern to utilities. Protection schemes shall work properly to identify and isolate faults quickly and minimize the impact on interrupting service to customers. This paper presents an analysis of a transformer neutral resistor damage on a low side bus fault utilizing fault records from digital fault recorders and digital relays to determine what and why happened. The fault records captured by the fault monitoring equipment and Sequence of Events provided valuable information which gave an insight into the nature of this event. The analog and digital data of fault records facilitate an efficient investigation and accurate analysis of this event.

System Overview and Incident Summary

S Street substation consists of three 115kV underground cables which each supply a 115/11.5kV transformer. The 115/11.5kV transformers are connected ground-wye at 115kV to resistor-grounded-wye at 11.5kV. The 11.5kV neutrals of all three 115/11.5kV transformers share a common neutral grounding resistor which is used to limit the 11.5kV ground fault current due to the rating of the underground cable system. Each 115/11.5kV transformer supplies a separate 11.5kV bus section - a total of three 11.5kV bus sections exist at this station. Each 11.5kV bus section consists of multiple supply cable and feeder positions using a double bus configuration with #2 Bus is normally energized and #1 Bus is normally de-energized. Back-to-back normally-open inter-bus tie breakers connect between the three 11.5kV bus sections. The 11.5kV system consists of six (6) 11.5kV supply cables and fourteen (14) radial 11.5kV feeders – each with current limiting phase reactors. The simplified substation one-line is shown in Figure 1.

On October 21st, 2014, the National Grid Distribution Control Center reported that:

At 10:06:16, an animal contact caused a C-phase-to-ground fault outside the Section 3 of 11.5kV #2 Bus between #3 transformer 11.5kV side 3T11 breaker and 3T11-1 and 3T11-2 disconnects at S Street (See Figure 1). Based on relay targets, sequence of event (SOE), digital fault recorder (DFR) and relay records:

- During the fault, the #1 and #2 Bus Section 3 bus differential ground (BDG, 87N) relays operated and picked up the bus lockout relays, but none of the #2 Bus Section 3 normally closed breakers at S Street tripped via the BDG lockout relay. Only the 11.5kV 1166 and 1168 network cable breakers tripped by the ground overcurrent (G, 51N) relays and the rest of #2 Bus breakers opened manually by Distribution Control Center (DCC) remotely and Operation & Maintenance (O&M) operators locally. Why did both #1 and #2 BDG relays sense the fault? And why did the #2 Bus breakers open manually?

- At the point of the DFR being triggered, current (both phase and ground) on the 115kV side of #3 transformer was about 100 amperes primary (CT Ratio = 400). 20 seconds later, the current jumped to over 1800 amperes primary, which matches the #3 transformer 115kV overcurrent (OC, 51) relay's record and short circuit simulation result without the common neutral resistor in service. The OC relay operated correctly in 6.5 cycles and the 11.5kV fault was finally isolated by tripping out the 115kV supply cable. By taking a close look at the SOE records, the fault lasted for over 41 seconds (See Table 1 in detail). How did the 115kV fault current increased in 18 times?

Due to the long duration of the fault, the common neutral resistor for #1, #2 and #3 transformers at S Street and some 11.5kV underground cables in the area 11.5kV network got damaged.

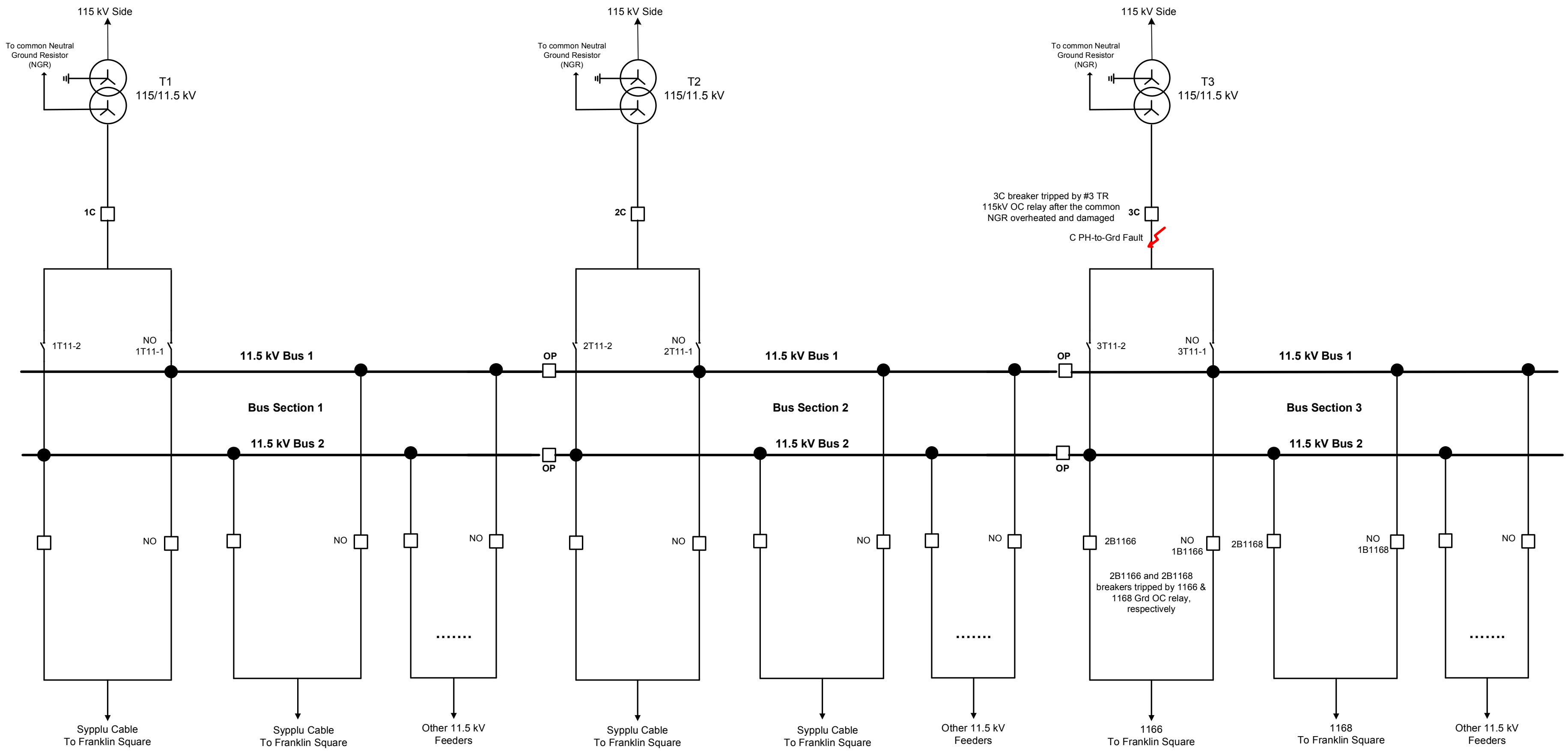

Figure 1. Simplified Substation One-Line Diagram and Fault Location

The DFR and the #3 transformer 115kV OC relay records are shown in Figure 2 & 3, the SOE record is listed in Table 1 and the relay targets reported for this event are as follows:

- 11.5kV Fault Detector of Bus Differential Ground (FDBDG)
- 11.5kV #2 Bus Section 3 Bus Differential Ground (Bus 2-3 BDG)
- 11.5kV #1 Bus Section 3 Bus Differential Ground (Bus1-3 BDG)
- 115kV #3 transformer Overcurrent (TR#3 OC)
- 11.5kV 1166 and 1168 Cable Ground Overcurrent (G)

Table 1. Sequence of Events for 2014-10-21 Event

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2014-10-21 10:07:00 SOUTH ST 11.5 3T11 ACB OPEN
2014-10-21 10:06:57.924SOUTH ST 11.5 3T11 ACB OPEN      #3TR 11.5kV breaker 3T11 opened at 10:06:57
2014-10-21 10:06:54 SOUTH ST 11.5 2B1164 OCB OPEN
2014-10-21 10:06:48 FRANKLINSQ 11.5 2T62 OCB OPEN
2014-10-21 10:06:48 FRANKLINSQ 11.5 1162 ACB OPEN
2014-10-21 10:06:45.984FRANKLINSQ 11.5 2T62 OCB OPEN
2014-10-21 10:06:45.975FRANKLINSQ 11.5 1162 ACB OPEN
2014-10-21 10:06:36 FRANKLINSQ 11.5 1139 AMPS Into LIM2HI zone 389.00 438.95
2014-10-21 10:06:36 FRANKLINSQ 11.5 1107 AMPS Into LIM2HI zone 275.00 305.60
2014-10-21 10:06:26 SOUTH ST 11.5 2B SECT 3 KV Into LIM2LO zone 11.10 10.93
2014-10-21 10:06:24 HARRISAVE 11.5 1430 OCB OPEN
2014-10-21 10:06:24 HARRISAVE 11.5 1430 OCB CLOSE
2014-10-21 10:06:24 HARRISAVE 11.5 1430 OCB OPEN
2014-10-21 10:06:24 HARRISAVE 11.5 1114 OCB OPEN
2014-10-21 10:06:24 HARRISAVE STATION TROUBLE ALARM
2014-10-21 10:06:23 DYER ST. 11.5 4205 OCB OPEN
2014-10-21 10:06:23 DYER ST. 11.5 1142 OCB OPEN
2014-10-21 10:06:23 DYER ST. 11.5 2B1102 OCB OPEN
2014-10-21 10:06:23 DYER ST. 11.5 1B1102 OCB OPEN
2014-10-21 10:06:23 DYER ST. 11.5 1106 OCB OPEN
2014-10-21 10:06:23 DYER ST. 11.5 1T06 OCB OPEN
2014-10-21 10:06:23 DYER ST. STATION TROUBLE ALARM
2014-10-21 10:06:21.494HARRISAVE 11.5 1430 OCB OPEN
2014-10-21 10:06:21.478HARRISAVE 11.5 1430 OCB CLOSE
2014-10-21 10:06:21.395HARRISAVE 11.5 1430 OCB OPEN
2014-10-21 10:06:21.393HARRISAVE 11.5 1114 OCB OPEN
2014-10-21 10:06:19.135DYER ST. 11.5 1T06 OCB OPEN
2014-10-21 10:06:19.126DYER ST. 11.5 1106 OCB OPEN
2014-10-21 10:06:18.902DYER ST. 11.5 1142 OCB OPEN
2014-10-21 10:06:18.900DYER ST. 11.5 4205 OCB OPEN
2014-10-21 10:06:18.576DYER ST. 11.5 2B1102 OCB OPEN
2014-10-21 10:06:18.575DYER ST. 11.5 1B1102 OCB OPEN
2014-10-21 10:06:20 SOUTH ST 11.5 2B1168 OCB OPEN
2014-10-21 10:06:20 SOUTH ST 11.5 2B1166 OCB OPEN
2014-10-21 10:06:16.994SOUTH ST 11.5 2B1168 OCB OPEN    Fault started at 10:06:16
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Investigation and Analysis

Prior to the event on 10/21/2014, S Street was under the normal configuration with the 11.5kV #2 Bus being energized carrying system load with all associated protection systems in service and #1 Bus being de-energized. No work crews were in the station at the time and the area was operating normally.

Based on the findings described above, the investigation focused on the three (3) following questions:

1. Why did both #1 and #2 BDG relays sense the fault?

2. And why did not the #2 Bus breakers open by #2 Bus Section 3 BDG relay but manually?

3. How did the 115kV fault current increased in 18 times and if resistor got damaged due to the long duration of the fault?

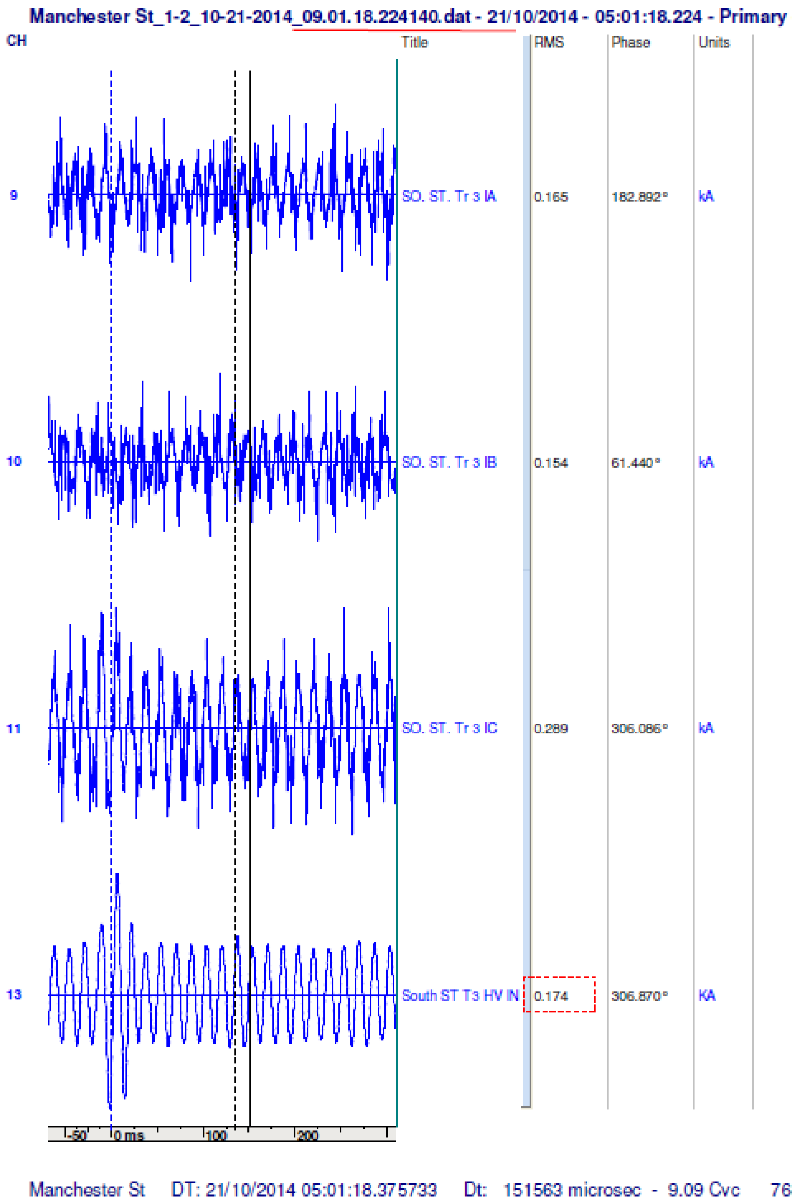

Figure 2. #3 115/11.5 kV Transformer DFR Records at S St. @ 10:06:18

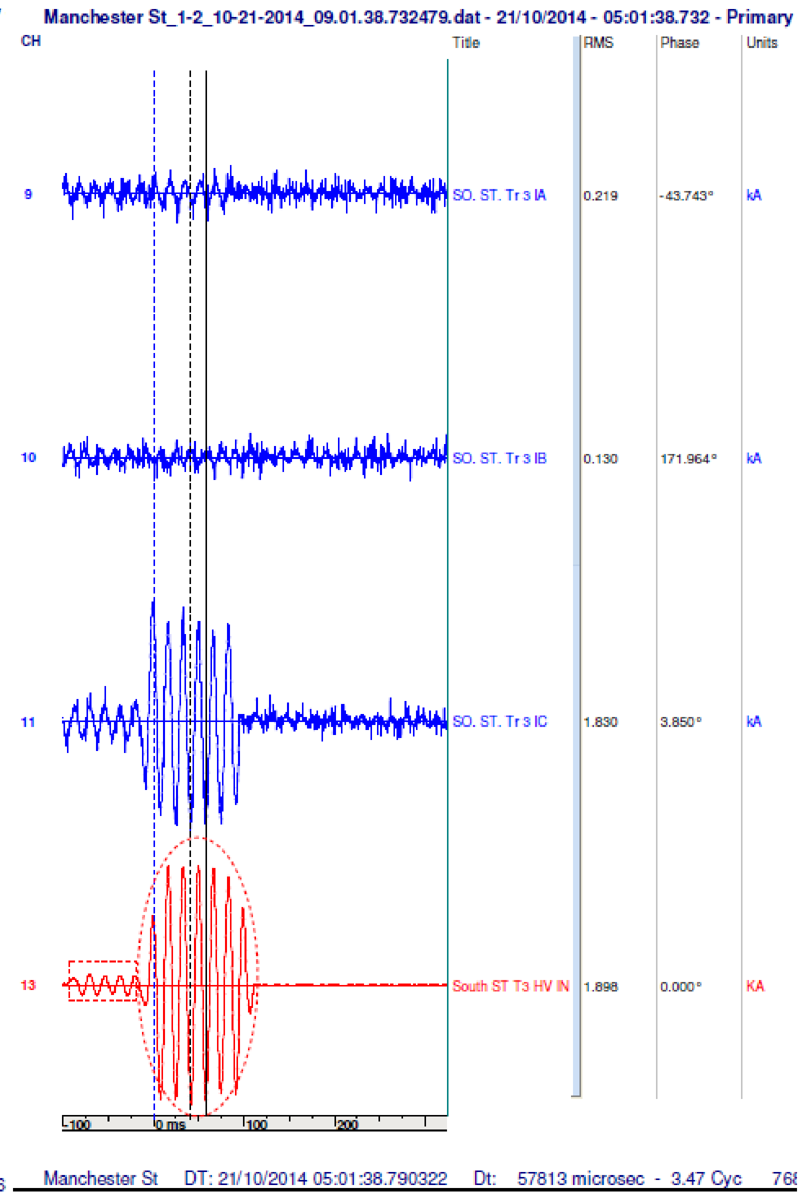

Figure 3. #3 115/11.5 kV Transformer DFR Records at S St @ 10:06:38

1. Why did both #1 and #2 Bus Differential Ground (BDG, 87N) relays sense the fault?

By reviewing the present design of current circuit for the #1 and #2 BDG schemes for all three sections, it is confirmed that each section of the #2 and #1 Bus BDG relay will respond to faults on the bus section of the #2 and #1, respectively, which is correct. However, for this particular fault location, it was inside the #1 BDG differential zone and outside the #2 BDG differential zone. Therefore, the #1 Bus Section 3 BDG operated per design. It appears that the #2 Bus Section 3 BDG operation was because some of CT's accuracy in the BDG circuit is relatively low and very likely resulted in CT(s) saturation during this fault. This #2 Bus BDG operation was incorrect but desirable for this fault.

Furthermore, according to the findings from this investigation, a design flaw on the #2 Bus Section 3 (apply to Section 1 and 2 as well) BDG was discovered. The CT for this BDG scheme is located on non #2 Bus side of the disconnect 3T11-2, which means the section between the 11.5kV breaker 3C and the CT is outside this BDG differential zone and so there is no BDG protection for this section under normal configuration at S Street. Although this section is covered by the #1 Bus Section 3 BDG scheme, nothing will trip via this scheme for faults within the section since #1 bus breakers are at normally open position. By the way, the #3 transformer differential zone ends up at the breaker 3C, therefore, there is no protection for the section between the 11.5kV breaker 3C and the CT located on non #2 Bus side of the disconnect 3T11-2 when the #2 Bus is in service. (See Figure 5 - Relay One-Line in detail) How to fix this problem?

2. Why did not the #2 Bus breakers open by #2 Bus Section 3 BDG relay but manually?

Test trips were performed by testing group on the #2 Bus Section 3 via the BDG scheme. The bus lockout relays did operate by the BDG scheme (same as during the 10/21/2014 fault), but only three of the 11.5kV breakers in the #2 Bus Section 3 tripped. It was determined that the lockout relays (HEA) did not operate to the full trip position. The HEA relays appeared to be mechanically bound, in another word, they didn't mechanically operate enough to trip the breakers. The HEAs were cleaned, lubed and operated several times. Further trip tests for the BDG scheme successfully tripped all 11.5kV breakers. The testing group also performed test trips on #2 Bus Section 1 and 2 and #1 Bus Section 1, 2 and 3 via their BDG scheme. Similar problem on the other 5 sections (totally twelve of lockout relays (HEA)) at S Street were caught up.

3. How did the 115kV fault current increased in 18 times and if resistor got damaged due to the long duration of the fault?

Per system design, the #3 transformer 115kV OC relay should not have sensed more than 100 – 150 amperes of fault current for an 11.5kV fault if the common neutral resistor on #1, #2 and #3 transformers at S Street connects and works as per design. Why did the fault current through the OC relay jump from 100 to 1800 amperes? The question was raised what was wrong with the neutral resistor? The short circuit simulation result confirmed that the fault current sensed by the #3 transformer 115kV OC relay matches the relay records if the common neutral resistor is by-passed. Based on this finding, it was suspected that the significant current jump was due to the slow fault clearing resulting in the neutral common resistor got damaged. Refer to Figure 2 and Figure3, the fault had been lasted for more than 20 seconds (10:06:18 – 10:06:38) and finally it evolved into a severe one. It was most likely the transformer 11.5kV common neutral resistor was bypassed and the zero-sequence fault current went through the earth directly.

Substation O&M inspected the common neutral resistor at S Street and confirmed that it was damaged due to over heat (see Figure 4), which explained why the current jump in 18 times after 40 seconds of the fault and, eventually resulted in the #3 transformer 115kV OC relay operated to isolate the fault from 115kV side.

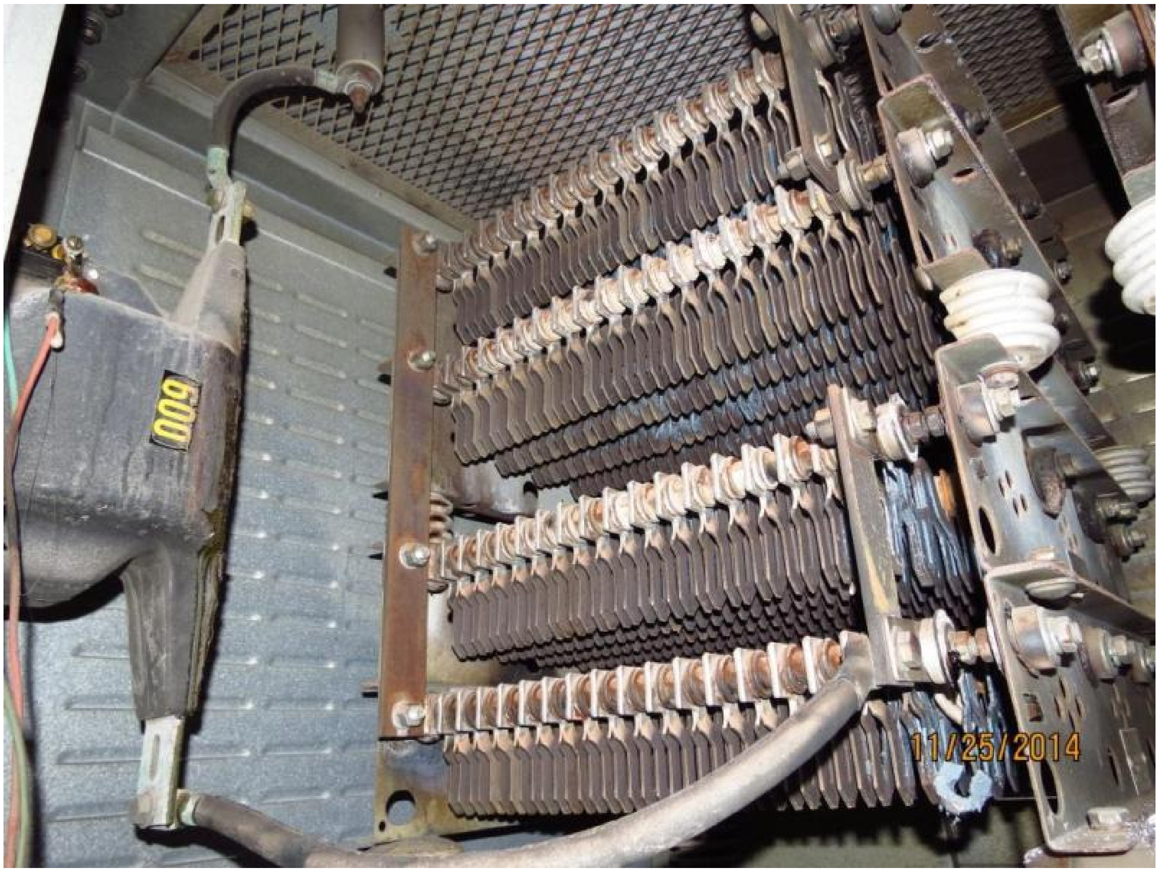

Figure 4. Damaged Common Neutral Resistor at S Street

Corrective Action Plan

Three corrective actions have been taken based on the above findings as follows:

1. The Damaged Common Neutral Resistor Issue: From the area 11.5kV underground network design perspective, none of #1, #2 or #3 transformer at S Street shall be put in service if no neutral resistor is in service. With the investigation team's support on specifying a new neutral resistor, the damaged resistor was replaced by Substation O&M within a month.

2. The BDG Lockout Relay Issue: The investigation team and testing group evaluated whether to replace all of BDG lockout relays at this time with taking into account the fact of this station is under rebuild. From a cost-effective and practical perspective, the testing group proposed to put these twelve lockout relays (HEA) under a maintenance program possibly every three months instead of replacing all twelve lockout relays now. This is an option because the station is being replaced within 2 - 3 years. Operating these relays every few months until the station is retired is probably less work overall than replacing them. If it is found that the lockouts are not working on a three month program NGRID would then have to replace them. The investigation team agreed with this proposal, and so the corrective action plan is to set up a maintenance program on the lockout relays (Twelve HEAs).

3. The #2 Bus Section 1, 2 and 3 BDG Design Flaw: It was evaluated whether NGRID shall take a risk on no protection for the section of between the 11.5kV breaker 1C, 2C or 3C and the CT located on non #2 Bus side of the disconnect 1T11-2, 2T11-2 or 3T11-2, respectively, when the #2 Bus is in service (Note: the #2 Bus is normally in service.). Investigation team also consulted to Control Center if the system configuration can be changed to run the #1 Bus normally in service. The response is no due to equipment rating issue. Given that the investigation team is strongly recommended to address this design flaw by correcting design if we want to improve the system reliability. The revised relay one-line for the corrective design is shown in Figure 6.

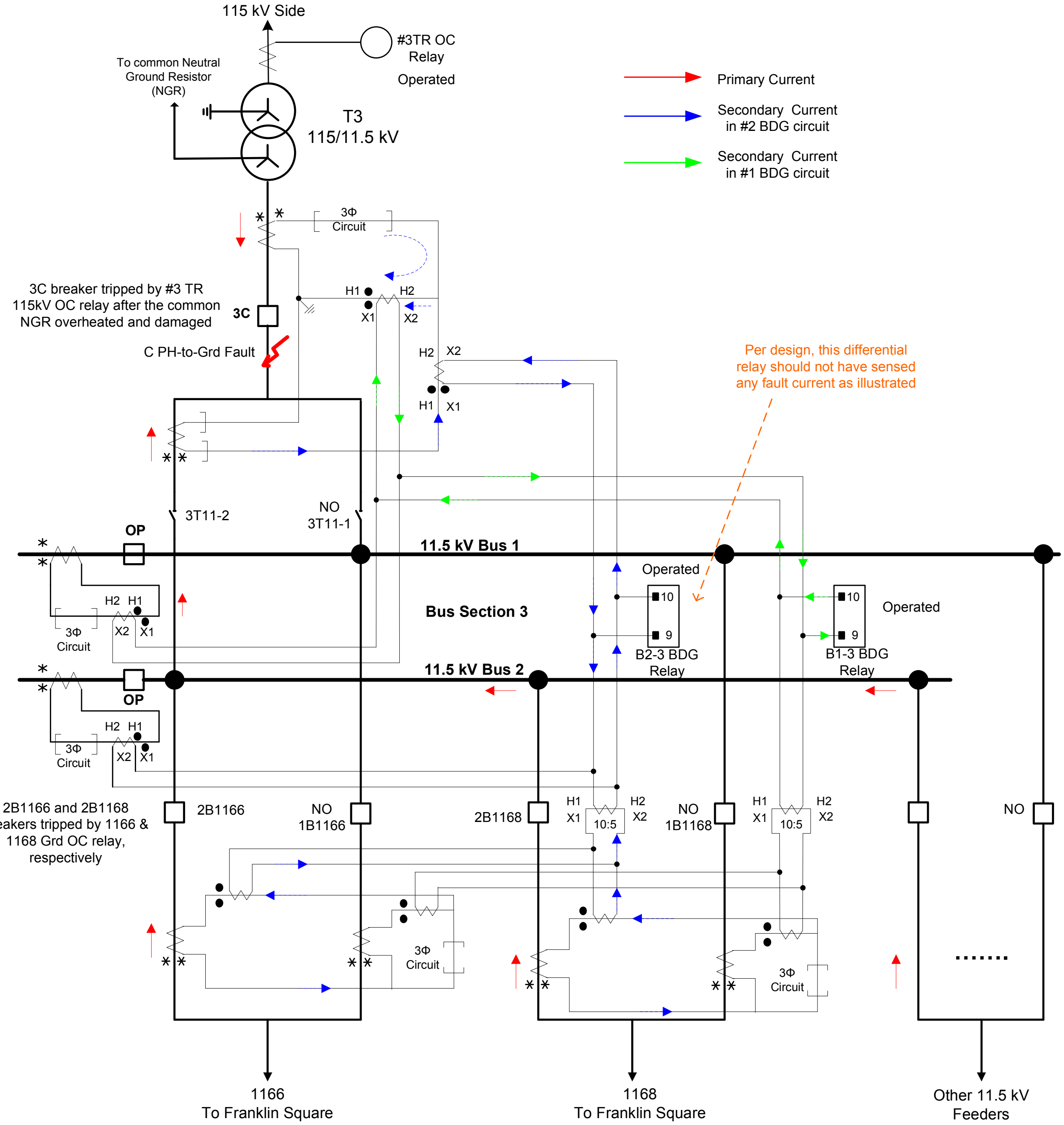

Figure 5. #1 & #2 Bus Section 3 BDG Relaying Current Circuit at S Street

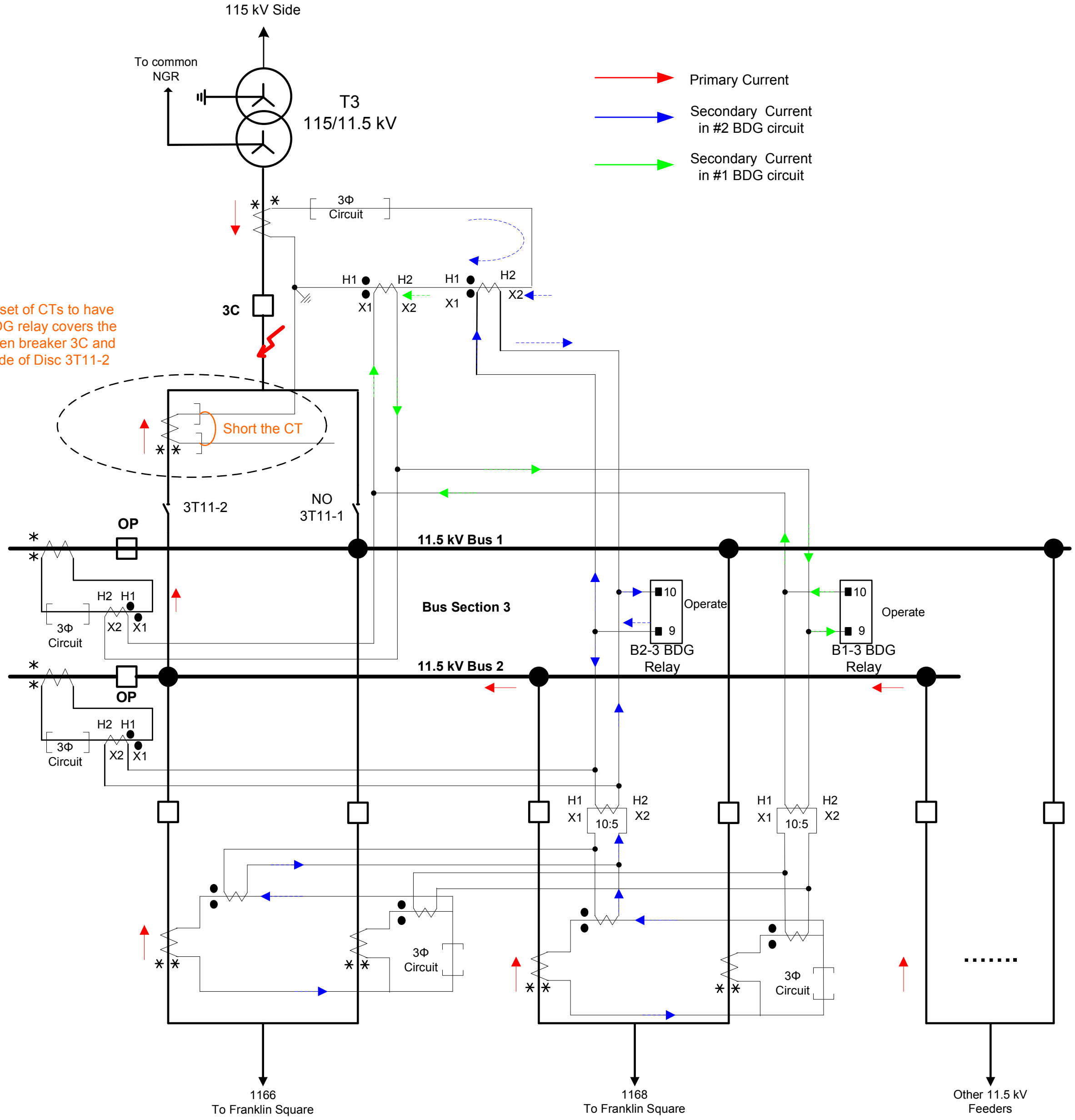

Figure 6. Mitigated #1 & #2 Bus Section 3 BDG Relaying Current Circuit at S Street

Summary and Closing Thoughts

Briefly recapping what we have discussed as follows:

- The #1 Bus Section 3 BDG operated per design, and the #2 Bus Section 3 BDG operation was because some of CT's accuracy in the BDG circuit is relatively low and very likely resulted in CT(s) saturation during this fault. This #2 Bus BDG operation was incorrect due to a design flaw in the BDG current circuit, but desirable for this fault. There is no protection for the zone between the 11.5kV breaker 3C and the CT located on non #2 Bus side of the disconnect 3T11-2 when the #2 Bus is in service. It is recommended to correct the design for all of six (6) Bus DBG schemes at S Street.

- It was determined that the BDG lockout relays (HEA) did not operate to the full trip position although the #2 Bus BDG relay picked up. The HEA relays appeared to be mechanically bound, in another word, they didn't mechanically operate enough to trip the breakers. This is the cause why the fault lasted for over 40 seconds.

- It was concluded that the significant through fault current jump was due to the slow fault clearing resulting in the neutral common resistor got damaged. From the area 11.5kV underground network design perspective, none of #1, #2 or #3 transformer at S Street shall be put in service if no neutral resistor is in service. The damaged resistor was replaced within a month.

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