Knoxville 161-kV Substation
Bus Insulator Failures and Corresponding Ground Problems

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On September 14, 2000 at 06:05 the Bus Differential relays, 987-2A and 987-2B, protecting Bus 2 at Knoxville 161-kV Substation operated and tripped Power Circuit Breakers (pcbs) 958, 968, 978, and 988 (see drawing 1). In addition, pcb 934 opened and reclosed due to the instantaneous operation of the back-up ground relay 9364. Fog was in the area when the trip occurred, but a review of Global Atmospherics' FALLS system showed that lightning was not a contributing factor. At 7:00 service was restored on Bus 2 with the closing of pcb 968. By 7:05 service on the Bus was completely restored. Station inspections did not indicate any bad insulators at this time.

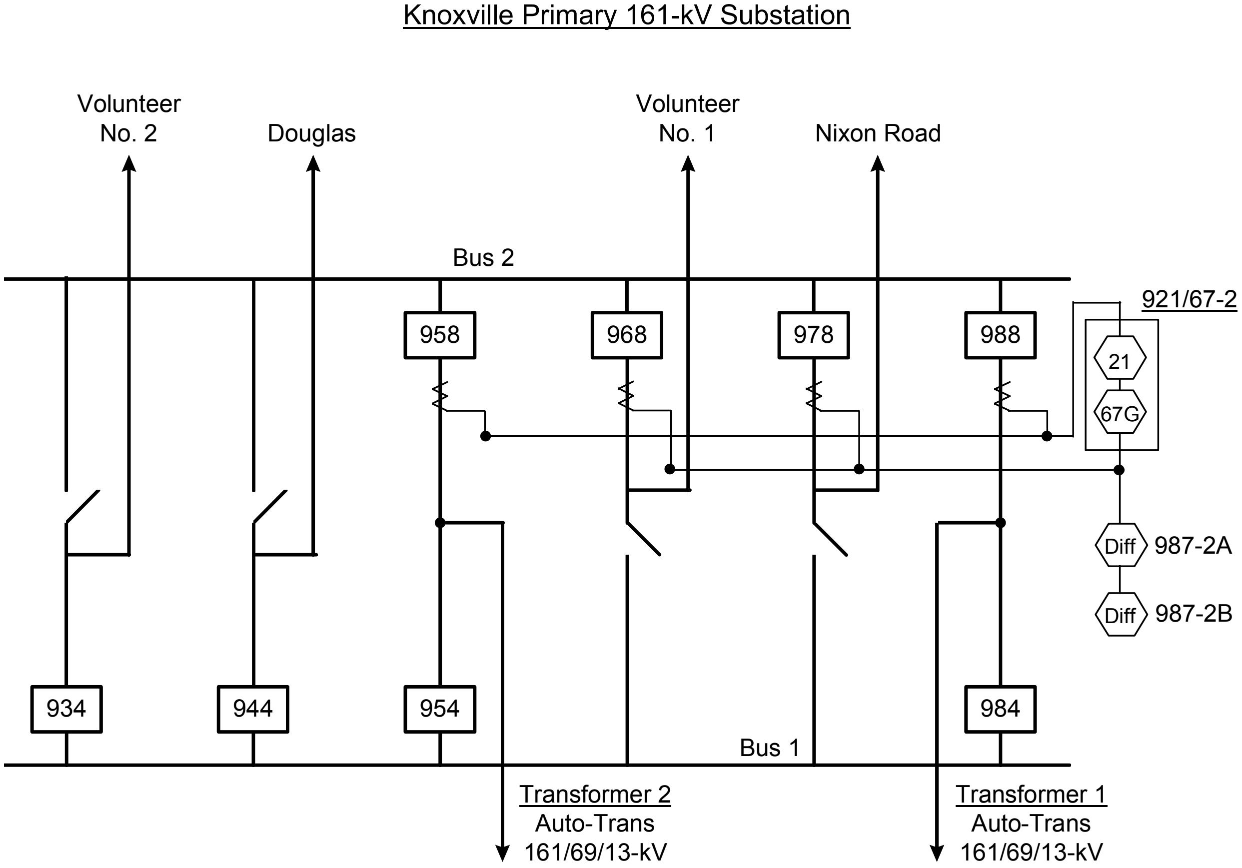

Figure 1: Knoxville Primary 161-kV Substation - Single Line Diagram

Oscillography at Knoxville Primary is recorded on a Rochester Instruments (RIS), 16 Channel, TR-1630. The recorder is set to monitor bus potential from Bus 1 (or Bus 2 through a selector switch), one line phase current and residual current from each of the four lines (2 phase currents are monitored on the Nixon Road line). In addition carrier traces are monitored on the two lines to Volunteer Substation.

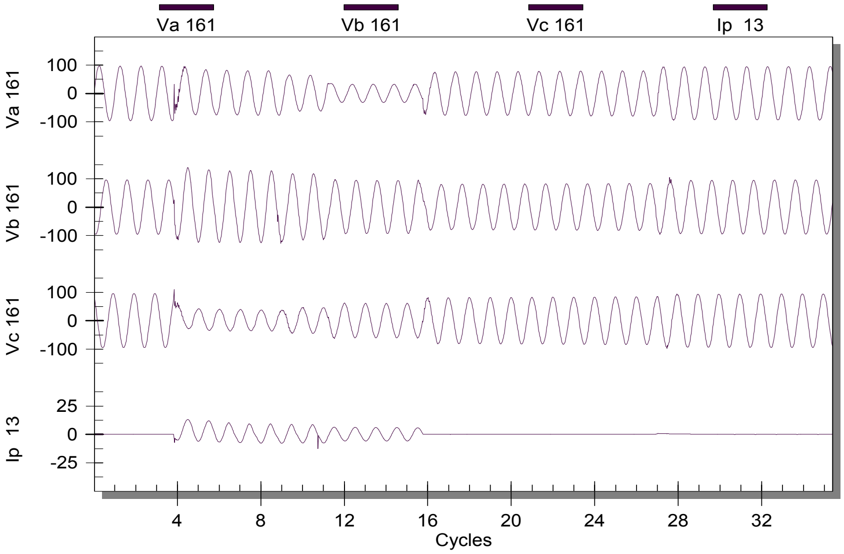

Figure 2: Bus Voltages and Polarizing Current for 9/14/2000 Bus Fault

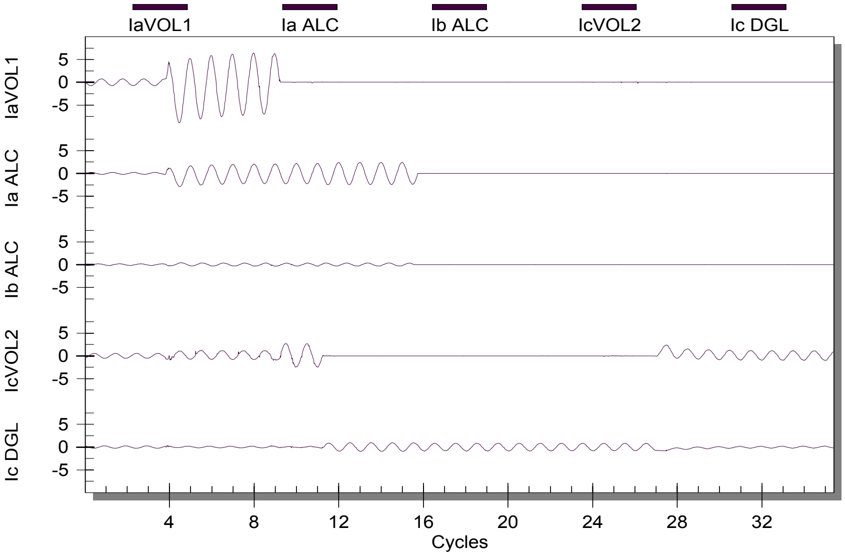

Figure 3: Line Currents for 9/14/2000 Bus Fault

The review of the oscillography for the event was complicated by apparent problems with the RIS 1630. While the Volunteer #1 A-phase current trace (IaVOL1) and the Nixon Road A-phase current trace (IaALC) seemed to indicate an A-phase fault (Figure 3), the bus potential traces (Figure 2) indicated that the fault originated on C-phase and migrated to A-phase coincident with the tripping of the Volunteer #1 161-kV line. A review of both digital and paper oscillography from surrounding stations substantiated the theory that the fault was caused by an A-phase insulator flash to ground and no C-phase involvement was observed.

Plans were made to perform a thorough wire check and calibration of the DTR. This work was performed but no discrepancies were found between the actual channel connections and those specified on the issued setting sheet.

On September 18 at 06:04, pcb 934 and 968 at Knoxville Primary tripped and reclosed successfully. Concurrent with these operations, pcb 854 tripped and reclosed at Volunteer 500-kV Substation, momentarily de-energizing the Knoxville-Volunteer #1 161-kV Line. Again, the RIS TR-1630 DTR at Knoxville Primary was queried (see figures 4 and 5) and again the data appeared misleading.

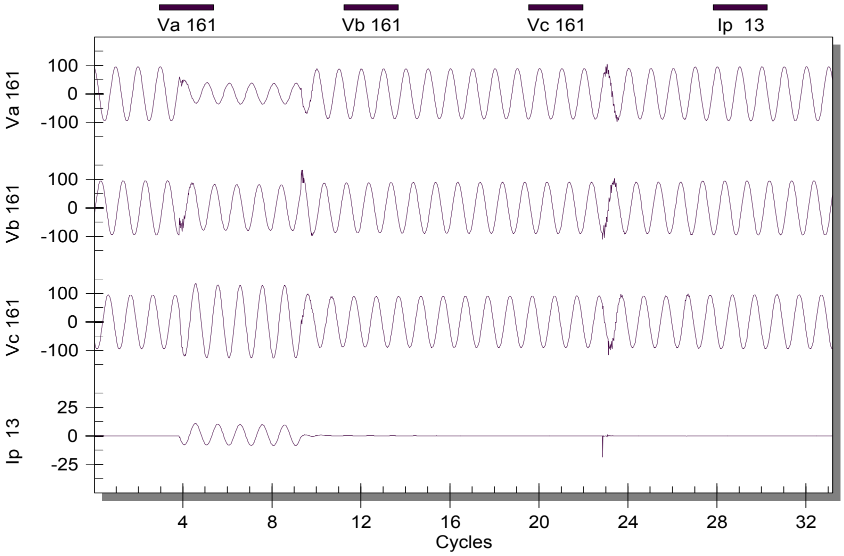

Figure 4: Bus Voltages and Polarizing Current for 9/18/2000 Bus Fault

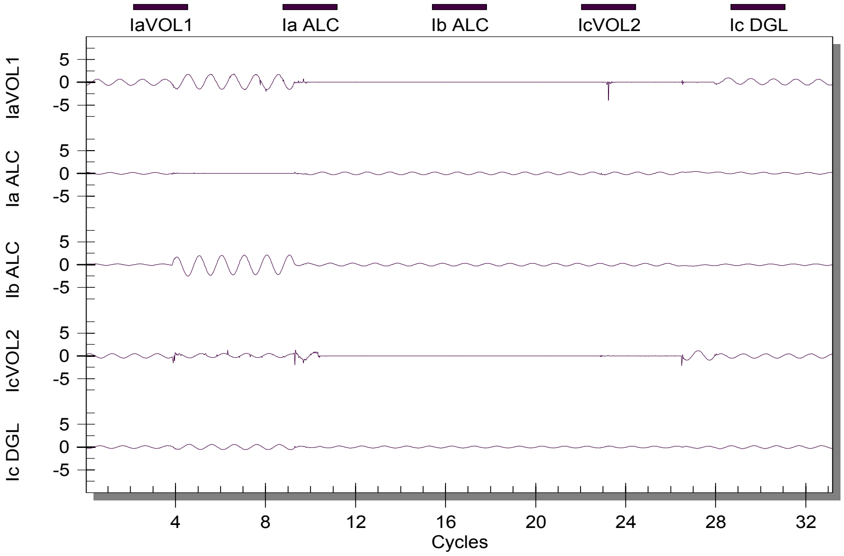

Figure 5: Line Currents for 9/18/2000 Bus Fault

While Figure 4 showed a definite collapse in A-phase voltage and a smaller decrease in B-phase voltage, the currents, shown in Figure 5, seemed to indicate a B-phase fault.

A review of oscillography from neighboring stations confirmed the existence of a B-phase fault. Further, a fault location study indicated that the fault was less than 5% of the distance from Knoxville Primary to Volunteer on the #1 Line.

The validity of the DTR data was again questioned and checks of the voltage channel connections were performed. This time the coupling capacitors voltage transformers (CCVTs) located on B-phase of the bus were utilized as a phase angle reference to confirm that the labeling on the auxiliary potential busses in the switch house were correct. As before, these tests did not reveal any abnormalities.

Concerns about the validity of the bus differential operation on September 14th in light of the apparent line related interruption on September 18th led local TVA and Knoxville Utility Board (KUB) management to take the Knoxville-Volunteer #1 Line out of service until a definite cause could be found for the interruptions.

On October 2, 2000 at 00:16, with the Knoxville-Volunteer #1 Line removed from service, operation of the Bus 1 Differential tripped and locked out pcbs 934, 944, 954, 984. Again oscillography recovered from the Knoxville DTR (Figures 5 and 6) tended to confuse the analysis of the actual event.

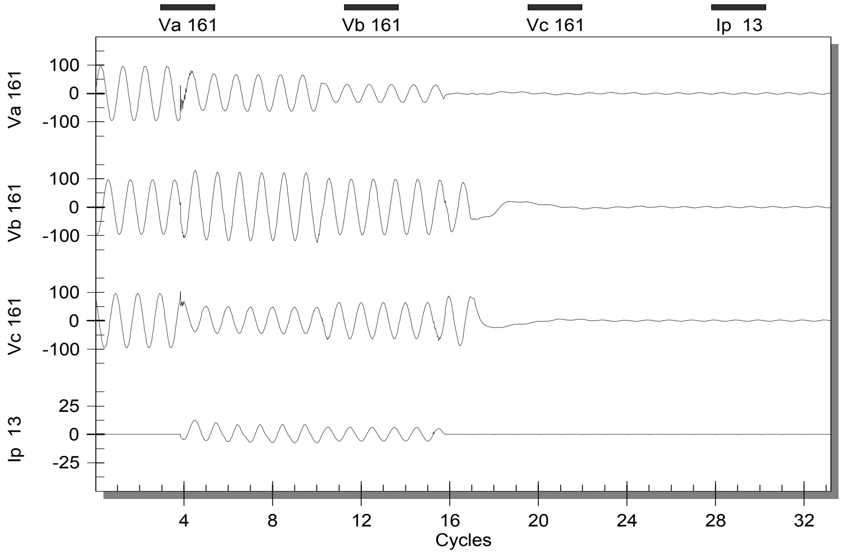

Figure 6: Bus Voltages and Polarizing Current for 10/2/2000 Bus Fault

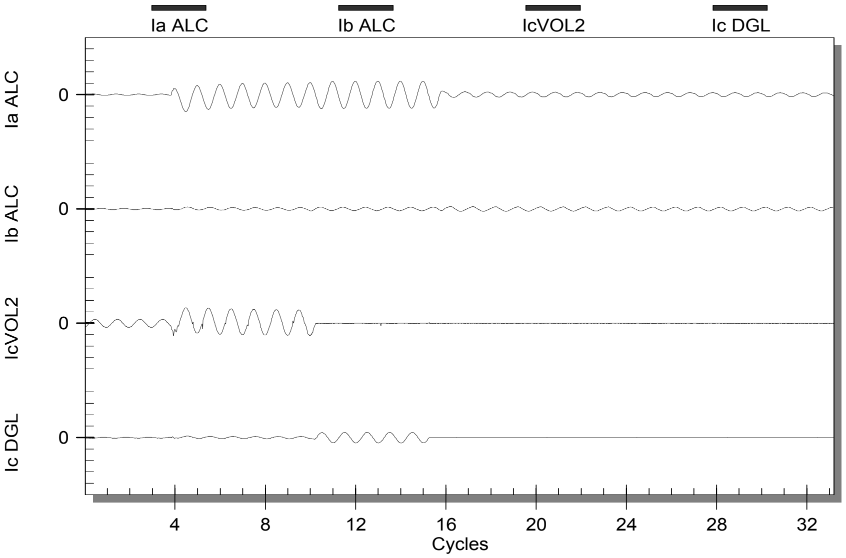

Figure 7: Line Currents for 10/2/2000 Bus Fault

With the exception that this fault involved Bus 1 and therefore the monitored Bus 1 voltage traces went to zero with the clearing of the fault, the voltage oscillography (figure 6) for the fault on October 2nd looked identical to that for the September 14th event (figure 2). Again, oscillography from surrounding stations showed the fault to be A-phase to ground with no other phase involvement.

Detailed Event Analysis

After numerous tests were conducted on the DTR at Knoxville and confirmed that the connections on the DTR were correct, a detailed analysis of the DTR data was undertaken. The purpose of this analysis was not to identify the cause of the fault but to identify the response of the recording equipment to the fault.

The first step in analyzing the data was to convert the raw DTR files into COMTRADE format. This was done to enable other analysis tools to be used. Another advantage to COMTRADE is the ease in which data can be modified and even created in the files. This was covered in a paper written by Jay Gosalia and Dennis Tierney and presented at the 2000 Fault and Disturbance Conference at the Georgia Institute of Technology in May 2000.

Because the fault type seemed to evolve with time, the voltages were examined at 2 times; 6 cycles and 14 cycles from the start of the fault record (Figures 8 and 9). (Prefault A-Phase voltage was used as the reference).

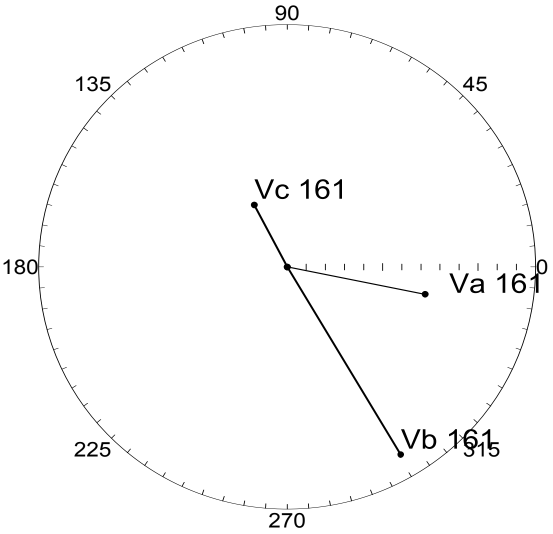

Figure 8: Voltage Vectors at t = 6 cycles on 9/14/2000

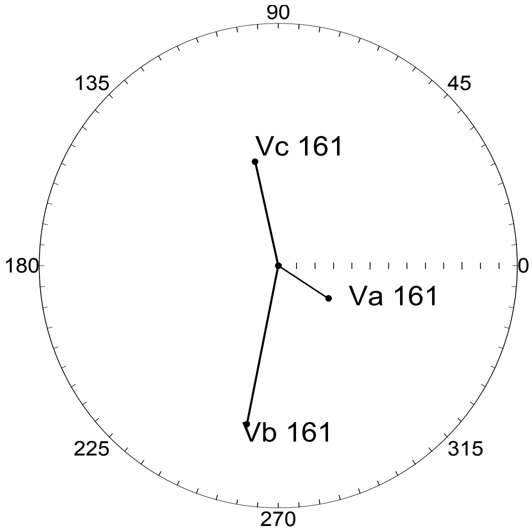

Figure 9: Voltage Vectors at t = 14 cycles on 9/14/2000

In analyzing the above vector data, $V_{a\ 161}$ or V_{ag} was dissected into two components; V_{an} and V_{ng} (see *Applied Protective Relaying* - Westinghouse, Chapter 2, Section IV.B.2). First V_{ng} was calculated:

$$V_{ng} = V_0 = (V_A + V_B + V_C) / 3$$

For the vectors in Figure 8:

$$V_A = 78.6\angle 348.5^\circ \text{ kV}$$

$$V_B = 124.7\angle 300.5^\circ \text{ kV}$$

$$V_C = 40.0\angle 117.4^\circ \text{ kV}$$

$$V_0 = (78.6\angle 348.5^\circ + 124.7\angle 300.5^\circ + 40.0\angle 117.4^\circ) / 3$$

$$= 50.0\angle 324.3^\circ \text{ kV}$$

Using COMTRADE the vector V_0 was able to be calculated and added into the phasor drawing. This was done by opening the "dat" COMTRADE file as a comma delimited file in EXCEL and adding the values from the three voltage channels (and dividing by 3). Microsoft Notebook was then used to modify the COMTRADE "cfg" file to reflect the addition of the new "channel". Adding this new vector to the illustrations shown in Figure 8 gave the following (figures 10).

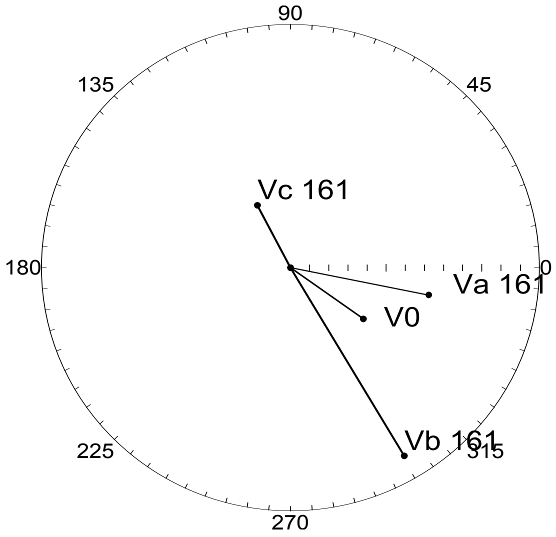

Figure 10: Voltage vectors on 9/14/2000 at t = 6 cycles with the calculated V_0

Similarly Figure 11 illustrates the V_0 (equal to $16.3\angle 297.6°$ kV) at t = 14 cycles.

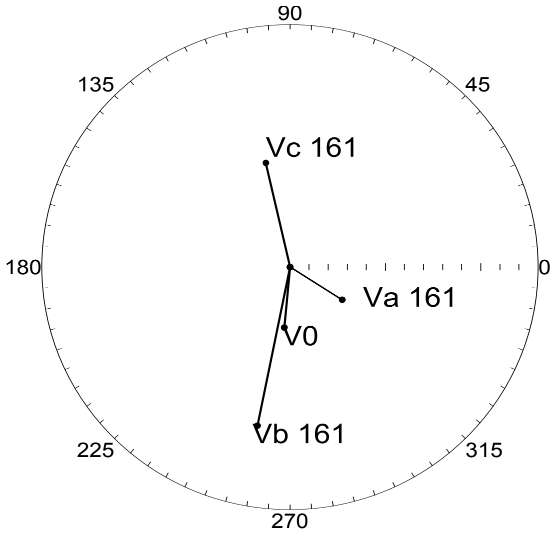

Figure 11: Voltage vectors on 9/14/2000 at t = 14 cycles with the calculated V_0

With V_0 now known, V_{an}, V_{bn} and V_{cn} (at t= 6 cycles) could be calculated:

$$V_{an} = V_{ag} - V_{ng}$$
$$= 78.6\angle 348.5^\circ - 50.0\angle 324.3^\circ$$
$$= 38.8\angle 20.4^\circ \text{ kV}$$

Similarly:

$$V_{bn} = 81.5\angle 286.2^\circ \text{ kV}$$
$$V_{cn} = 87.6\angle 132.4^\circ \text{ kV}$$

V_{an}, V_{bn} and V_{cn} were then plotted, again using COMTRADE, by removing the V_0 component from the observed phase to ground voltages. This led to the more recognizable vectors of a single-phase to ground fault shown in Figure 12.

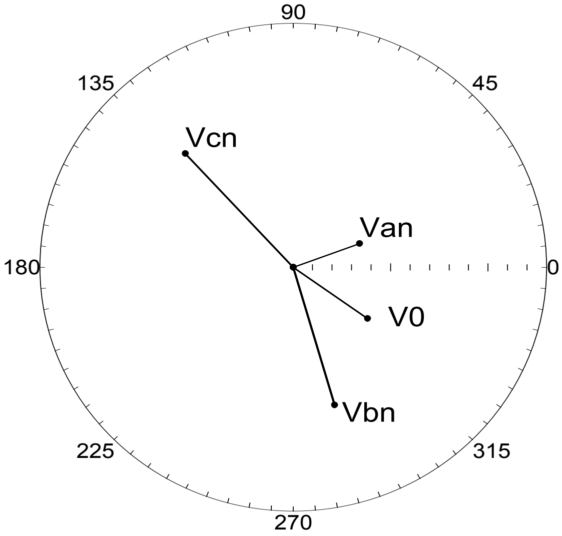

Figure 12: Voltages for 9/14/2000 fault after compensation at t = 6 cycles

In like manner the voltages were calculated for the fault values at t = 14 cycles:

$$V_{an} = 28.8\angle -2.5^\circ \text{ kV}$$
$$V_{bn} = 76.4\angle 257.3^\circ \text{ kV}$$
$$V_{cn} = 76.8\angle 99.0^\circ \text{ kV}$$

These vectors, again indicating the A-phase to ground fault are shown in Figure 13.

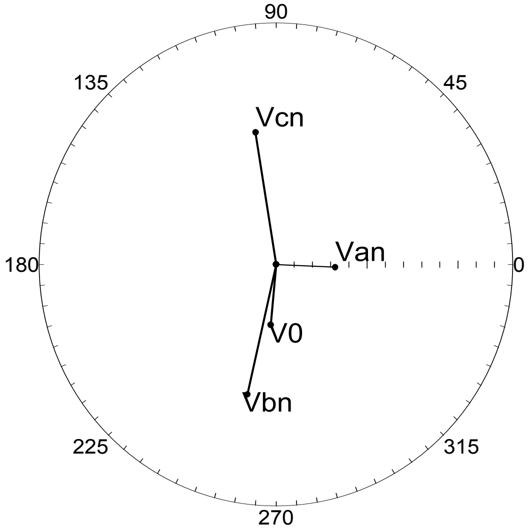

Figure 13: Voltages for 9/14/2000 fault after compensation at t = 14 cycles

Similar methods were then applied to the fault on 9/18:

$V_A = 36\angle 305.2^\circ$ kV

$V_B = 83.5\angle 184.8^\circ$ kV

$V_C = 122.1\angle 130.5^\circ$ kV

$V_0 = 50.8\angle 158.3^\circ$ kV

Therefore:

$V_{an} = 83.4\angle 324.6^\circ$ kV

$V_{bn} = 44.3\angle 215.7^\circ$ kV

$V_{cn} = 80.7\angle 113.4^\circ$ kV

The uncompensated and compensated phasor diagrams for this fault are shown in Figure 14. These verify that the fault was B-phase to ground as suspected from surrounding oscillography.

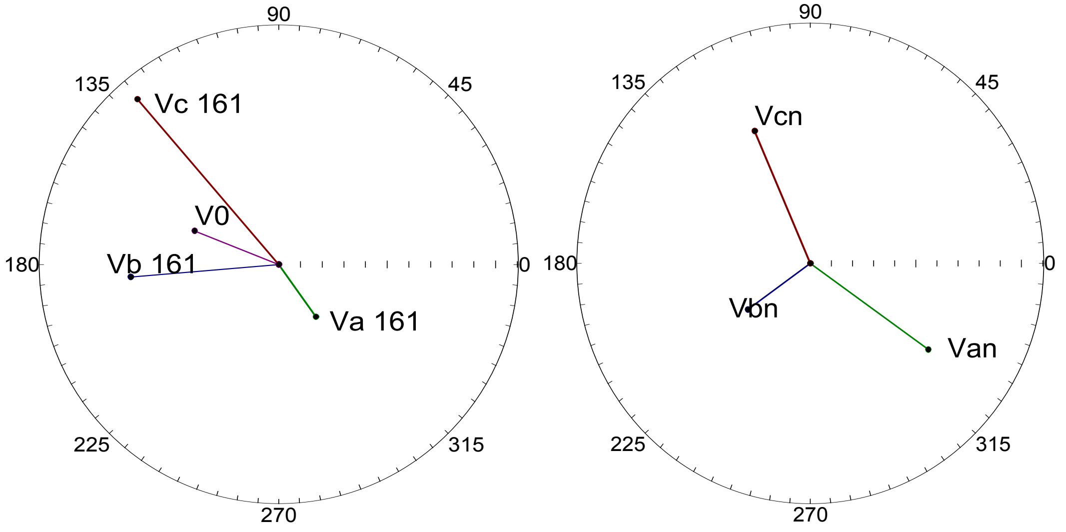

Figure 14: Uncompensated and compensated bus voltages for fault on 9/18/2000

Finally, these methods were applied to the bus differential operation on 10/2. Again, due to the changing nature of the fault two times were selected for analysis.

At t = 6 cycles:

$V_A = 64.5\angle 346.2^\circ$ kV

$V_B = 117.6\angle 293.8^\circ$ kV

$V_C = 50.2\angle 121.3^\circ$ kV

$V_0 = 38.7\angle 316.4^\circ$ kV

Therefore:

$V_{an} = 36.4\angle 18.1^\circ$ kV

$V_{bn} = 83.2\angle 283.6^\circ$ kV

$V_{cn} = 88.1\angle 127.9^\circ$ kV

At t = 14 cycles:

$V_A = 32.7\angle 333.2^\circ$ kV

$V_B = 96.4\angle 266.9^\circ$ kV

$V_C = 64.5\angle 108.6^\circ$ kV

$V_0 = 16.7\angle 273.8^\circ$ kV

Therefore:

$V_{an} = 28.1\angle 3.9^\circ$ kV

$V_{bn} = 79.9\angle 265.4^\circ$ kV

$V_{cn} = 80.7\angle 105.6^\circ$ kV

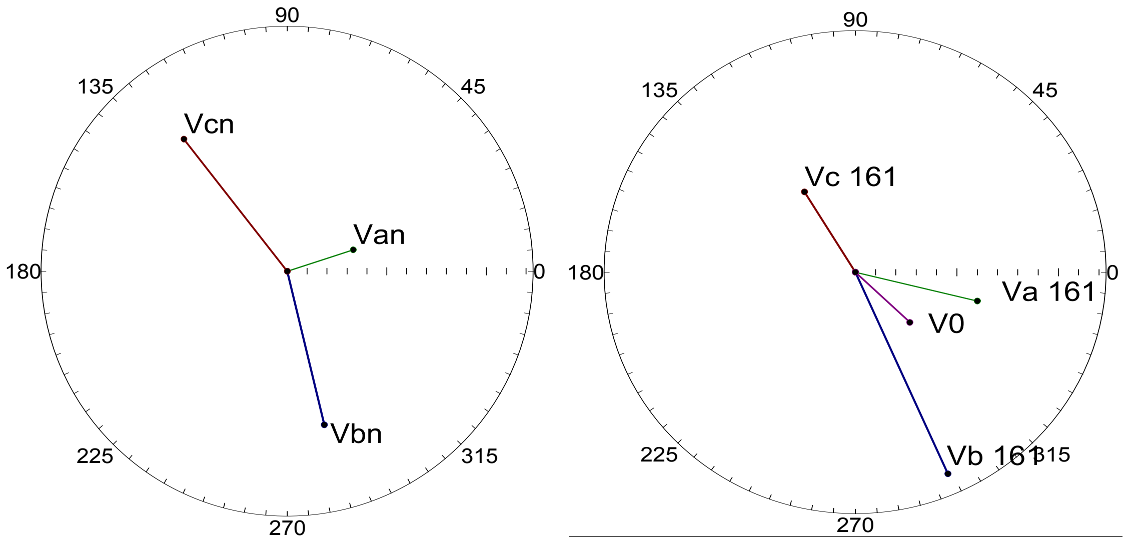

Figure 15: Uncompensated and compensated bus voltages for 10/2 fault at t = 6 cycles

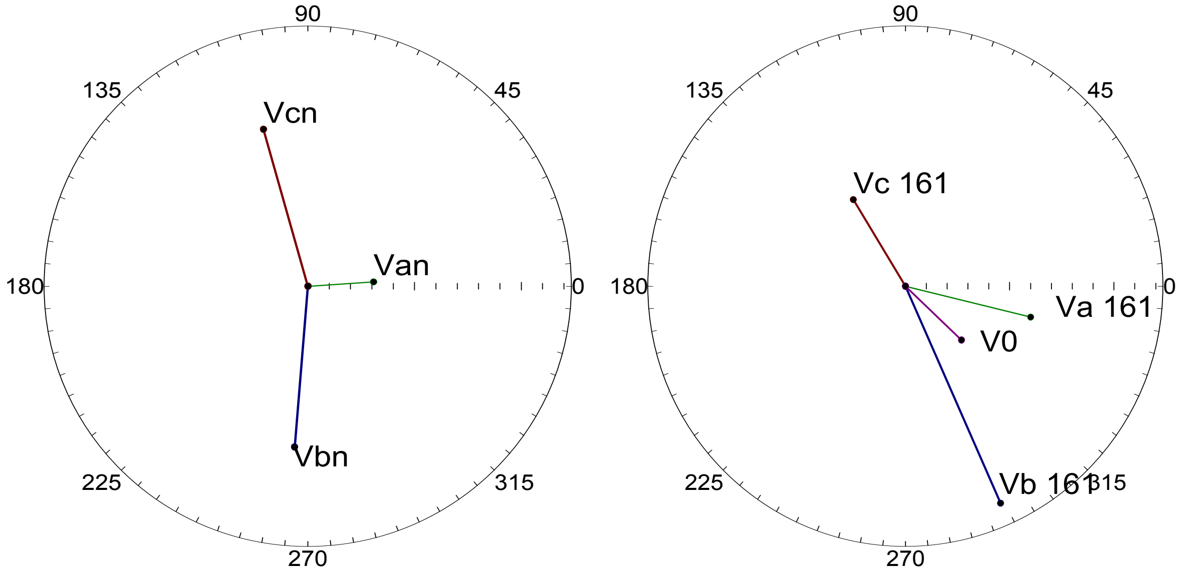

Figure 16: Uncompensated and compensated bus voltages for 10/2 fault at t = 14 cycles

Conclusion

By using COMTRADE and other tools to dissect and manipulate the bus voltage values present during these three faults, the true nature of the faults was revealed. The above analyses showed that the actual faults were normal, single phase to ground faults, whose nature was hidden by large offset voltages. With this knowledge, a very detailed, thorough investigation was made of the station which revealed that two insulators in the bay associated with breaker 968 had flash damage. Comparison with the other bays in the station showed that this bay had a particular type of insulator that was different than the other bays and was no longer used at TVA. As a result the bus-work in the bay was taken down and new insulators were installed. Two additional benefits were also realized; the connections and operation of the DTR were confirmed and a potential problem with the station grounding was uncovered.

Epilogue

In February 2002, test personnel performed ground mat connectivity tests at Knoxville Primary. Using a 12V automotive battery, dc ammeter and current limiting resistor, each piece of station equipment was verified to be tied to the station ground mat. The only abnormally high resistance reading was found on a switch ground plate and was caused by the plate being painted with non-conductive paint. This situation was corrected. No other investigations are planned at this time.

Tim Burgess graduated in 1984 with a B.S.E.E. from Texas A&M. He started working for the Tennessee Valley Authority in 1986 with TVA's Nuclear Group as a construction engineer. Later that year he transferred into substation maintenance as a substation test engineer. In December 1993 he transferred to TVA's central office in Chattanooga to begin working in the Protection and Analysis Group as a Post Fault Analysis Engineer. Recently Tim transferred out of the central office and assumed the duties of Transmission Maintenance Manager for the Chattanooga area of TVA.