ROOT CAUSE ANALYSIS FOR CENTER SUBSTATION 138 kV CIRCUIT BREAKER EVENT ON JANUARY 16, 2012

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1. Introduction

On Monday, January 16, 2012 the 138 kV West Bus Tie Circuit Breaker at the Center Substation experienced an internal phase to ground fault. This circuit breaker consists of three single phase interrupting tanks, a common operating mechanism and a control cabinet. The top of the middle tank, B phase, was breached and the control cabinet doors were ejected. This event caused an oil spill and fire in the substation. The fire in the control cabinet burned until power could be disconnected and then the fire was put out. Labels shown on Figure 1-1 identify key components of the circuit breaker discussed in the root cause analysis.

IPL conducted a root cause analysis for this event to determine causes and corrective actions. This report presents these findings and recommendations.

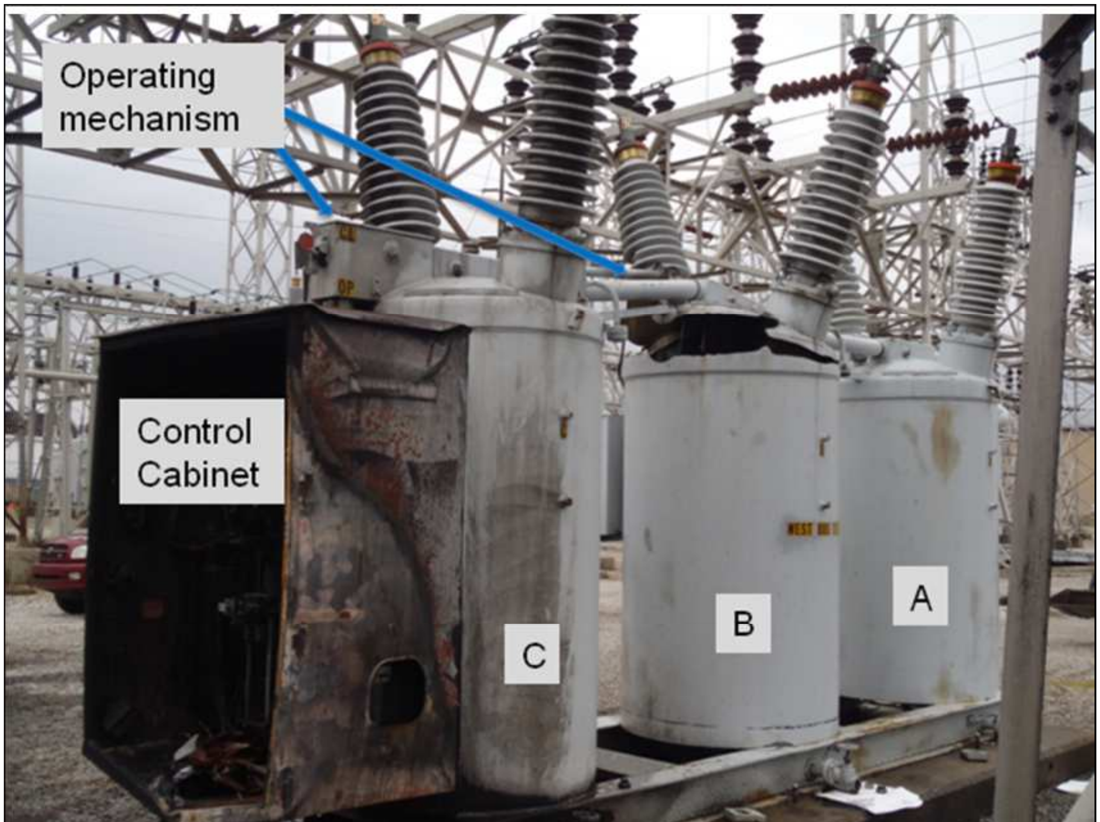

Figure 1-1 Center Substation circuit breaker after the event

2. Background

The Root Cause Analysis Team reviewed maintenance history on this circuit breaker since 2004. However, focus was put on the most recent maintenance activities.

On September 30, 2010 ductor readings, a measurement of contact resistance, were taken and indicated a need for internal maintenance on this circuit breaker. A new work order for an internal inspection was issued on September 30, 2010. No written documentation was found confirming that an internal inspection was ever completed corresponding to this work order. The last time the Circuit Breaker had a similar problem, cleaning and replacing the contacts did not appear to provide a long term solution. Therefore, IPL planned to replace the springs in addition to the contacts.

Repair parts were ordered on August 8, 2011, and they were delivered September 6, 2011. An infrared measurement on January 4, 2012 showed abnormal heating in two tanks. Figure 2-1 shows the infrared scan. Previous experience indicated that at these observed temperatures the circuit breaker did not require immediate repair. Maintenance to replace contacts and springs was scheduled in coordination with a planned outage for other equipment.

Operating conditions were normal for the time of year.

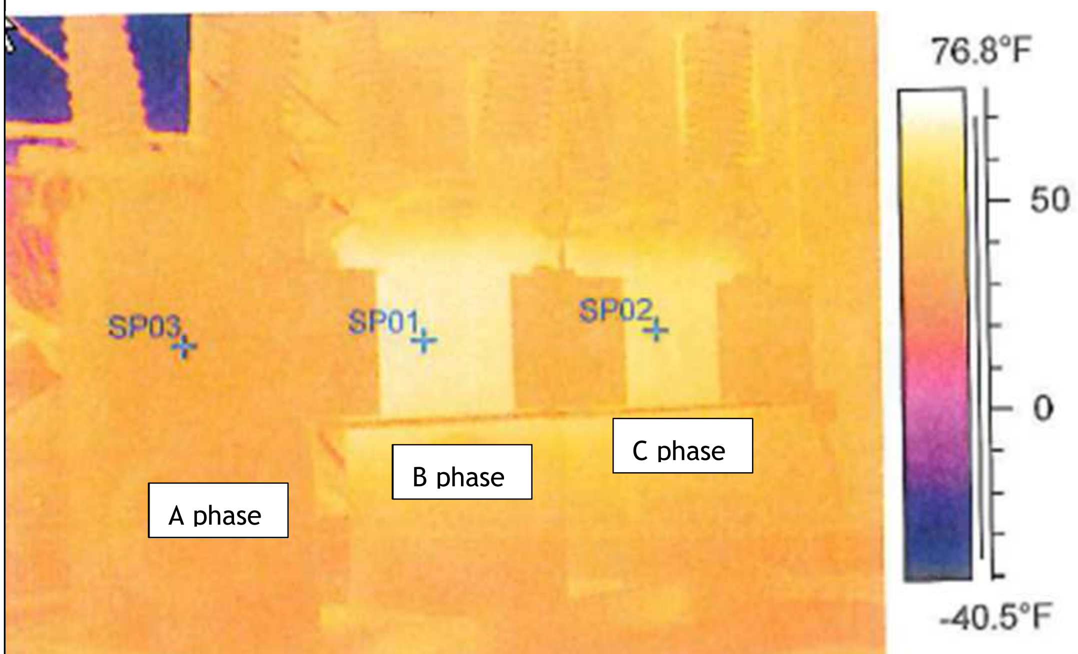

Figure 2-1 Infrared report from January 4

3. Sequence of Events

Date / TIME (EST)	EVENT
9/14/04	Center Substation 138kv West Bus Tie Breaker Infrared Scan shows C phase tank 27.9 degrees F over ambient.
2/17/06	Center Substation 138kv West Bus Tie Breaker Infrared Scan shows C phase tank 32.5 degrees F above ambient.
3/14/06	Center Substation 138kv West Bus Tie Breaker Internal inspection performed based on 2/17/06 infrared report. Cleaned interrupters.
4/10/06 to 4/12/06	Center Substation 138kv West Bus Tie Breaker Doble test performed, ductor readings indicate breaker is in good condition.
4/25/06 to 11/22/06	Center Substation 138kv West Bus Tie breaker, took DGA monthly tests.
9/30/10	Center Substation 138kv West Bus Tie Breaker Ductor readings indicate excessive resistance in contacts.
8/8/11	Parts ordered (springs, buttons, contacts) for Center Substation 138Kv West Bus Tie Breaker.
9/6/11	Parts received to replace contacts and springs for Center Substation 138Kv West Bus Tie Breaker.
1/4/12	Infrared picture of Center Substation 138kv West Bus Tie Breaker taken showing B phase tank 35 degrees F over ambient. C phase is about 30 degrees F over ambient.
1/5/12	Oil quality samples taken from Center Substation 138kv West Bus Tie Breaker and sent to lab in anticipation of planned maintenance. (Results returned back normal 1/16/12 on day of event).
1/16/12 for subsequent sequence items (Day of event).	
10:39:25	System operator commands Center Substation 138kv West Bus Tie Breaker to open. Confirmed by ECS and subsequent analysis.
10:39:26	Center Substation 138kV West Bus Tie Breaker unauthorized reclose reported by ECS
10:39:50	System operator command Center Substation 138kv West Bus Tie Breaker to open. Confirmed by ECS.
10:40:17	System operator command Center Substation 138kv West Bus Tie Breaker to close. Close confirmed by ECS.
10:41:43.700	Neutral current starts to rise on the remote end terminal of the Line fed by this breaker. (Determined from after the fact analysis).
10:46:02.500	The remote end terminal B phase of the Line begins intermittent conduction as measured by Phasor Measurement Unit. (Determined from after the fact analysis).
10:46:06.358	First trigger of oscillograph at an adjacent Substation on neutral current on a separate Line.
10:46:08.500	The remote end terminal B phase of the line intermittent conduction stops with zero current. Neutral current stabilizes at 472 amperes.
10:50:22.900	The remote end terminal of the Line sees intermittent conduction on B phase again.
10:50:55.000	The remote end terminal of the line sees B phase intermittent conduction stop with zero current in B phase. Neutral current stabilizes at 472 Amperes.
10:51:03	System operators acknowledge and erase several oscillograph alarms

Date / TIME (EST)	EVENT
11:04:39.000	Center Substation 138kv West Bus Tie Breaker, B phase to ground short circuit starts (beginning of visible event). Relays begin sending trip signals to circuit breakers, Center Substation 138Kv East Bus Tie Breaker, Center Substation 5 other Line Breakers, and the remote end terminal of the line (138Kv Breakers 3B and 3C).
11:04:39.100	A phase current and C phase current go to zero on the remote end terminal of the Line.
11:04:39.191	Center Substation 138 kV bus clears. Center Substation F-Unit outage begins for 5,845 customers.
11:04:39.200	C phase short to ground begins, B phase involvement continues as seen from the remote end terminal.
11:04:39.599	Fault current at the remote end terminal goes to zero as the breakers open (end of short circuit event).
11:04:40	Center Substation H-Unit outage begins for 3,541 customers.
11:08	Service restored to all customers by load transfers to Center Substation F-Unit.
11:13:31	Begin de-energizing equipment for fire department. Center Substation F-Unit and H-Unit outages for 9,386 customers.
11:18:32	Center Substation, all equipment de-energized for fire department. Fire department extinguishes remaining fire.
11:47	Center Substation F-Unit and H-Unit back in service. Customers restored.

4. Investigation and analysis

The investigation and analysis contains two parts. The first section, 4.1 is the physical observations of conditions after the event. The second section, 4.2 presents a pictorial re-creation of the event based on a detailed root cause analysis.

4.1. Physical observations of conditions after the event

Careful inspection of the physical condition damage found the following conditions:

1. Internal arc between the B phase live parts and side of the tank with contacts destroyed
2. Breaker position indicator found in a half open position
3. Top of B phase tank breached directly above location of internal fault
4. Top of C phase tank had small breach at connection support to B phase tank with minor burning of contacts
5. Evidence of flashover between C phase disconnect switch and ground at the base of the switch
6. No evidence of internal fault to ground inside the C phase circuit breaker
7. Control cabinet doors found near fence
8. Hydraulic pump motor end cap dented (pump is housed inside the control cabinet)
9. Thermostat above the motor end cap bent upward
10. Damage from extended burning inside cabinet
11. Control cabinet distortion is consistent with high pressure event inside the cabinet
12. Approximately 1/3 of the insulating oil from the B phase tank was expelled in a westerly direction (approximately 275 gallons)
13. Carbonized oil residue on the side of the building

4.2. *Pictorial representation of the event progression*

This section provides a visual perspective of the events as they unfolded. The shaded area in some pictures provides an accurate representation of the oil plume migration during the sequence.

Figure 4-1 10:46:02.500 Contact degradation

After a maintenance circuit breaker operation was completed at 10:39:25.000 B Phase intermittent conduction begins at 10:46:02.500 as shown in Figure 4-1.

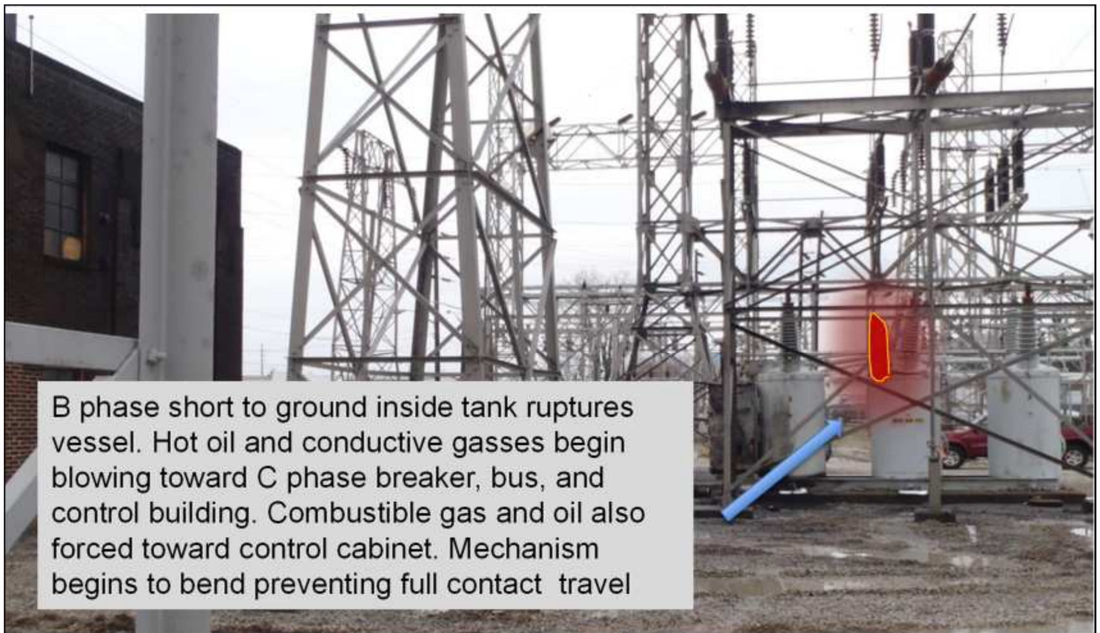

Figure 4-2 11:04:39.000 B phase internal fault

At 11:04:39.000, live parts inside the B phase tank shorted to ground. The internal pressure breached the B phase tank. It also forced oil and gasses through the operating mechanism into the control cabinet. Figure 4-2 shows the beginning of the breach. The upward movement of the top of the B phase tank begins at about this time.

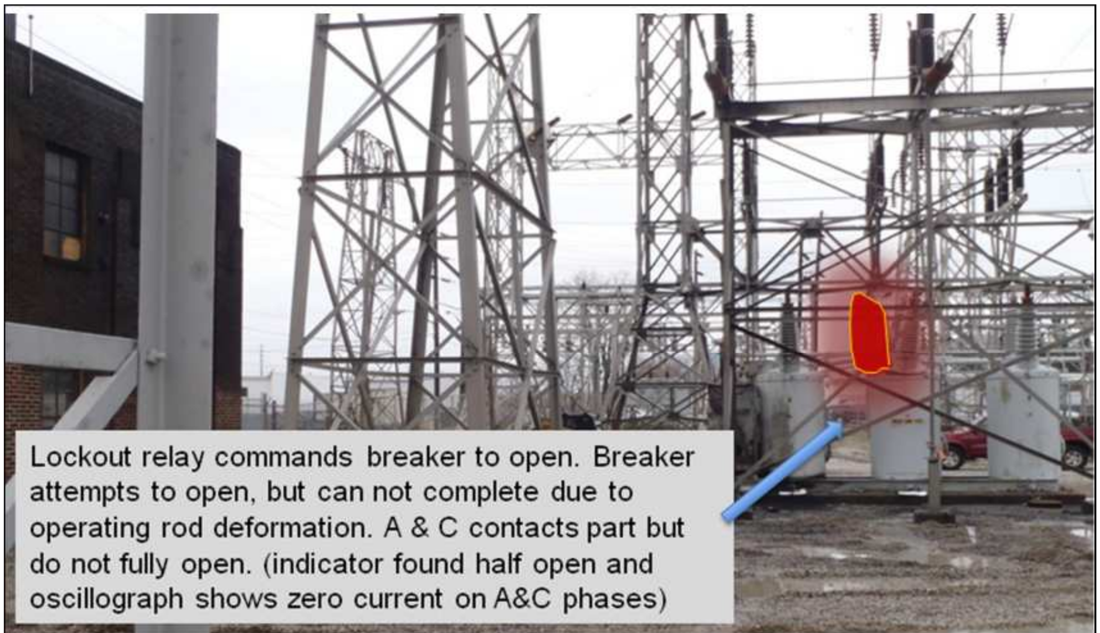

Figure 4-3 11:04:39.1 Lockout sends trip

By 11:04:39, a bus protection lockout relay sends trip commands to this circuit breaker and other circuit breakers at the substation. The breaker attempts to open but is stalled as the operating mechanism that spans across the top of the three tanks continues to deform. Data confirms the A and C phase current stopped flowing. The breaker indicator shows half open position after the event. Figure 4-3 shows the approximate migration of the oil and gases.

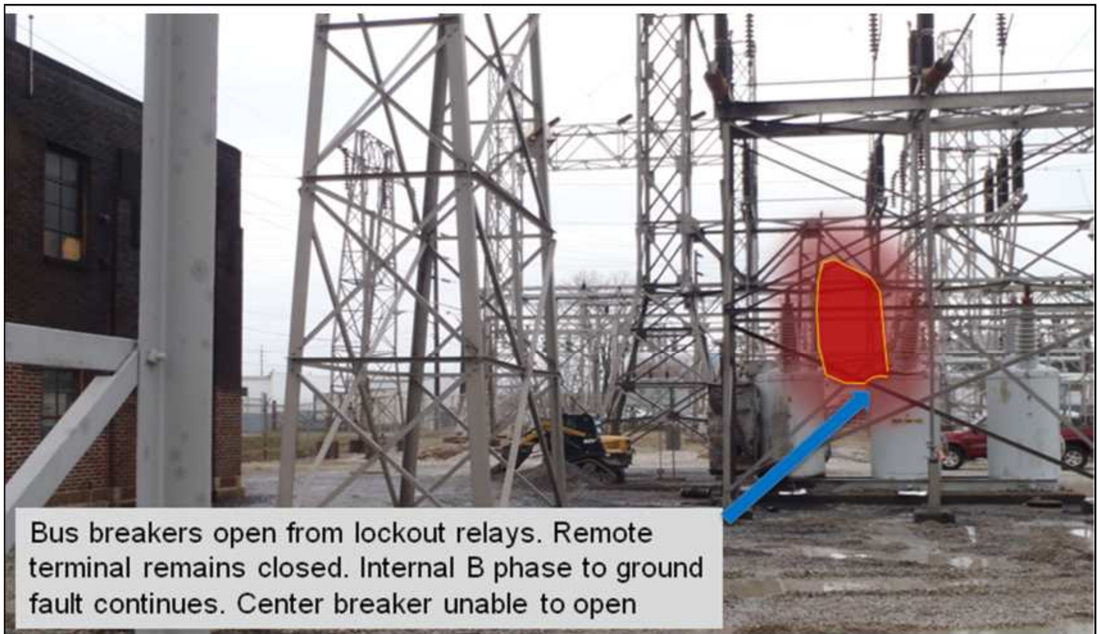

Figure 4-4 11:04:39.191 Bus breakers open

At 11:04:39.191 all other bus breakers open. The remote end terminal has not yet cleared. C phase line disconnect switch is not yet involved as seen in Figure 4-4.

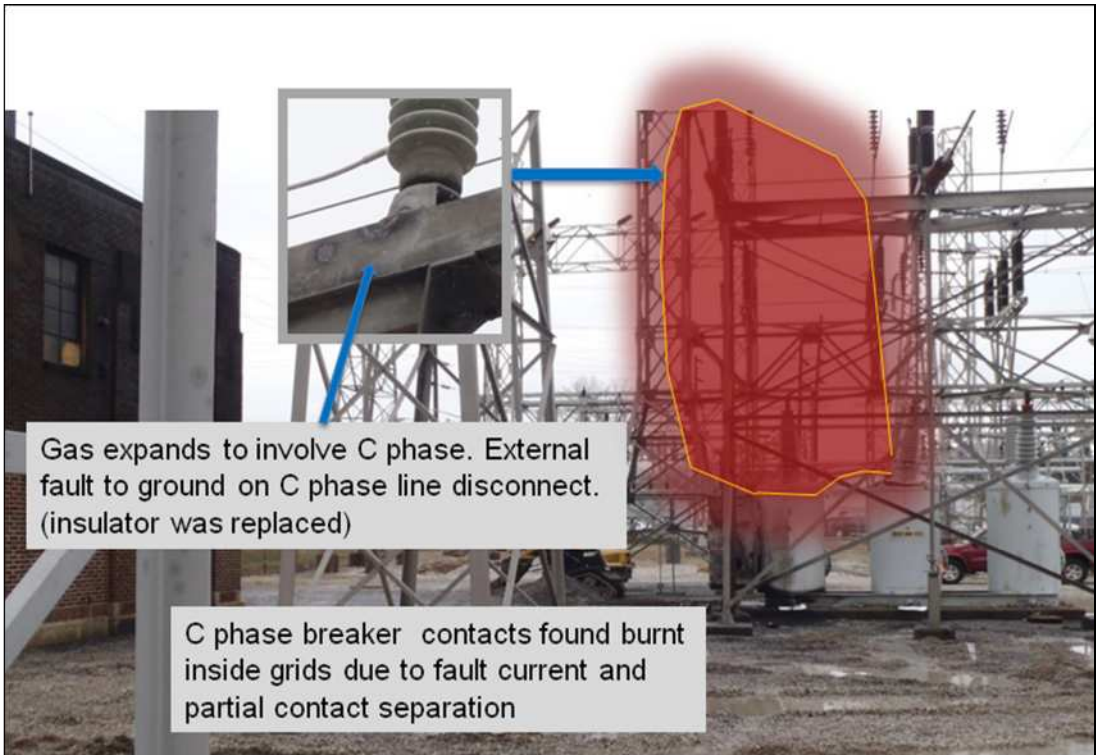

Figure 4-5 11:04:39.2 C phase fault starts

By 11:04:39.2, the conductive gasses and carbon in the oil envelop the C phase bus disconnect causing an external C phase to ground short circuit in addition to the internal short circuit on B phase . Figure 4-5 shows the migration of gasses into the C phase bus disconnect. Figure 4-5 also shows the burn mark at the bottom of the disconnect switch. Inspection inside the C phase tank confirmed no internal short to ground. It should be noted that this second short circuit was a result of the event. It did not affect the amount of oil dispersion, fire or equipment damage.

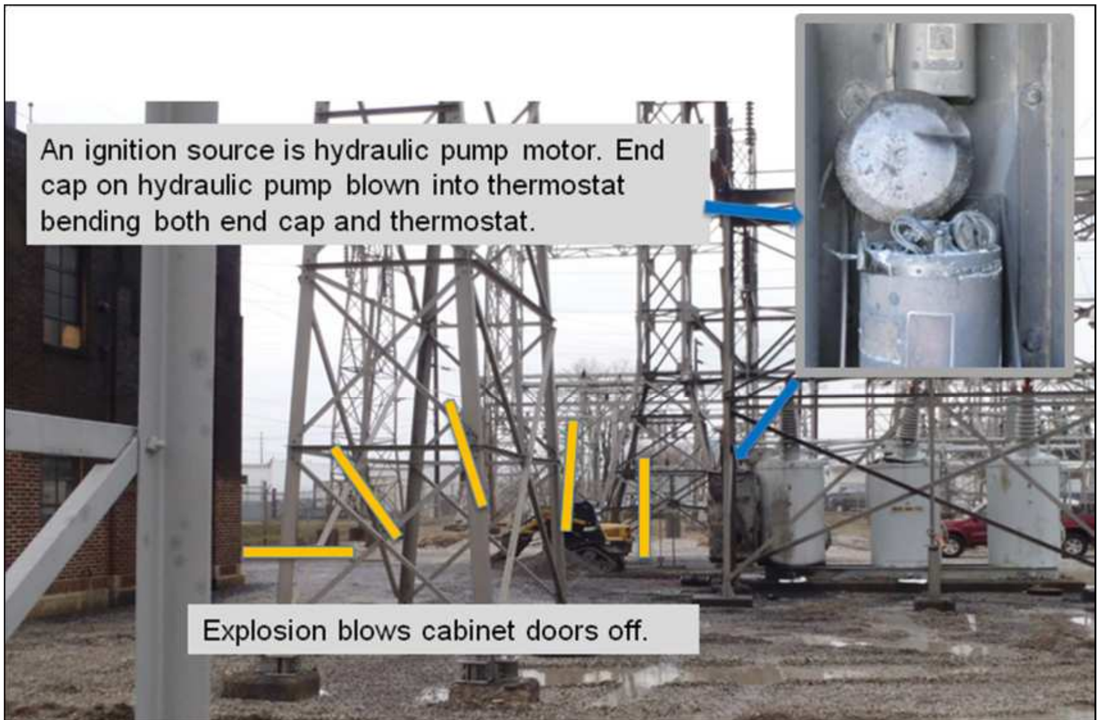

Figure 4-6 Sometime after 11:04:39.000 the control cabinet doors blow off to the fence

Sometime during the event there was a second source of ignition inside the circuit breaker mechanism cabinet causing the doors to blow off. The hydraulic pump motor attempted to run either due to control or vibration when B phase tank breached. A run switch inside the motor apparently ignited gases and blew the end cap into the thermostat. The end bell of the motor was in the bottom of the cabinet. Figure 4-6 shows the motor, the dented end cap and the thermostat. The thermostat is bent upward consistent with a blow from the end cap.

5. Findings

The root cause analysis found Physical Roots, Human Roots, and Latent Roots. The definitions of these are given. These three different types of root causes may be closely interrelated. Physical Evidence and Miscellaneous Findings and Observations are also listed

Physical Root: A cause that explains how the failure had occurred physically and involves tangible materials.

Human Root: A point of inappropriate human intervention.

Latent Root: The lack of, or deficiency in, management systems (rules, procedures, guidelines, etc.) or restraining cultural norms that allowed the failure to occur.

5.1. Physical root causes

1. B Phase to ground fault due to deteriorated contacts in the circuit breaker.
2. Arcing inside B Phase Circuit Breaker caused creation of flammable gases.
3. Linkage pipe transported combustible gases from B Phase circuit breaker to control cabinet.
4. Hydraulic pump motor was a source of ignition and was a secondary event inside the control cabinet.
5. C Phase to ground fault at switch due to conductive gas expulsion from B Phase tank and the remote end terminal remaining energized.
6. Primary relays were out of service due to a lack of communication from pilot cables.
7. Bent linkage from B Phase Circuit Breaker caused breach on C Phase Circuit Breaker.

5.2. Human root causes

1. Ductor readings could have been in error since they contained 5 digits instead of 4.
2. Infrared report lists criteria for open air switches not circuit breakers.
3. Maintenance work was not effectively prioritized.
4. Significant time elapsed between inspection in September 6, 2010 and the scheduled maintenance planned for April, 2012.
5. Pilot wire maintenance is superseded by other maintenance activity.
6. Operation of a circuit breaker when maintenance is pending could result in a catastrophic event.
7. Operator inadvertently superimposed two data point names (at Castleton and Center substations).
8. C Phase fault may have been avoided if pilot wire was operable allowing the primary relaying to trip more quickly than the backup relaying.

5.3. Latent root causes

1. No formal maintenance trigger criteria for ductor readings for circuit breaker resistance.
2. No formal maintenance trigger criteria for infrared readings on circuit breaker temperatures.
3. Maintenance record keeping processes and requirements not clearly established.
4. Previous experience with this breaker indicated that repairs were not urgent.
5. No cross reference to prevent operation of circuit breaker if maintenance is pending.

6. Automated asset management software tools not implemented.
7. Difficult to switch at Center substation due to design and operational issues.
8. Waiting for other equipment to be off line for planned maintenance.
9. Circuit high loading limits the ability remove equipment from service for maintenance at Center substation.

5.4. Physical Evidence

1. Ductor readings obtained September 10, 2010 showed high values for B phase.
2. Experience has shown that ductor readings can be improved if circuit breaker is operated.
3. Infrared on January 4, 2012 showed B phase hot (35 degrees F over ambient).
4. Internal and External marks on B phase tank show source of internal fault.
5. Arcing inside B Phase Circuit Breaker created combustible gases.
6. B Phase circuit breaker breached causing top of breaker to be opened directly above fault marks inside circuit breaker.
7. Relaying showed that B Phase faulted first.
8. Circuit breaker indicator found to show that it was half open.
9. Picture clearly shows linkage tore C Phase circuit breaker top.
10. Contact arcing due to contacts not being fully closed.
11. Arcing inside C Phase interrupter caused fiberglass debris on contact.
12. C Phase to ground fault evidence found near line side disconnect.
13. No written data as to why contacts and springs were ordered for replacement in B Phase circuit breaker.
14. Contacts and/or springs were worn.
15. Contacts and springs were ordered September 30, 2010 and received September 6, 2011.
16. Contacts and springs were scheduled for replacement April 2012.
17. Ductor reading records are suspect because 5 digits were entered instead of 4 digits.

5.5 Miscellaneous Findings and Observations

1. The circuit breaker operated successfully for about two years (2004-2006) with approximately 30 degrees F over ambient.
2. The breaker was maintained in 2006 and monitored subsequent to the maintenance.
3. Inspection data indicated the breaker needed maintenance again in September of 2010. It appeared to be a similar situation as recorded in 2004.
4. Pilot wire relaying was out of service causing slow tripping from the remote end terminal. However this did not materially affect the event outcome.
5. The System Operator operated the wrong circuit breaker while performing the maintenance practice of exercising circuit breakers.
6. Training is needed to ensure work is scheduled aligned with new clearly asset management criteria.

6. Recommendations

The root cause analysis team recommends the following actions:

1. Establish formal infrared and ductor criteria to trigger maintenance priorities.
2. Improve readability of maintenance spreadsheet that contains list of circuit breakers to be operated for the month.
3. Create review process to check for outstanding maintenance before issuing maintenance cycling orders to System Operations.
4. Develop a plan to return primary relaying to normal operation.
5. Improve documentation of substation maintenance records.
6. Fully utilize automated asset management tools specifically designed for substation maintenance.
7. Allocate resources and implement tools to assure that substation maintenance activity is adequately tracked a prioritized efficiently.
8. Implement a procedure to track all work scheduling delays and ordering of parts to avoid delays in required maintenance of equipment.
9. Document process for field data review and subsequent work flows.

7. Team Members

Thomas Pottschmidt, P.E. – Principal Analyst

Larry Conrad, P.E. – Consultant

Steve Clouse, P.E. – Principal Engineer, Reliability

John Emrich – Senior Engineer, Relay/SCADA

David Leonard – Section Leader, Network and Substation Operations

Joan Soller, P.E. – Manager, Transmission Operations

Eric Stevenson – Work Scheduler, Network and Substation Operations

8. Appendix A

Data Collected | Completed On

CIRCUIT BREAKER TEST RESULTS:

Dissolved Gas Analysis	02/01/12
Infrared Pictures	02/01/12
Relay Testing Records	02/01/12
Oil Test Results	02/01/12

TIMELINE INPUT:

Breaker Operation Schedule	02/02/12
ECS System Data	02/14/12
Hold Cards for 2006	02/01/12
Audio Logs	02/01/12
Log Sheets	02/01/12

RELAYING INFORMATION:

Oscillograph Recordings of Incident	02/01/12
Ground Relay Data	02/01/12
Static Burn Down Data	02/08/12
Current (Amperes) Study	02/01/12
Test Subject Relay at Center Sub	02/08/12

MAINTENANCE DATA:

Maintenance Performance Analysis & Review Report	02/08/12
Circuit Breaker Maintenance File	02/01/12
EMPAC Maintenance Records	02/01/12
W.O. History	02/01/12

PARTS:

New Parts (springs and contacts)	02/08/12
Remains of Circuit Breaker	02/02/12

MISCELLANEOUS:

Environmental Report	02/08/12
Purchase Order	02/29/12
Substation Drawing	02/01/12
Phase Diagrams	02/01/12
Pictures of Incident	02/01/12