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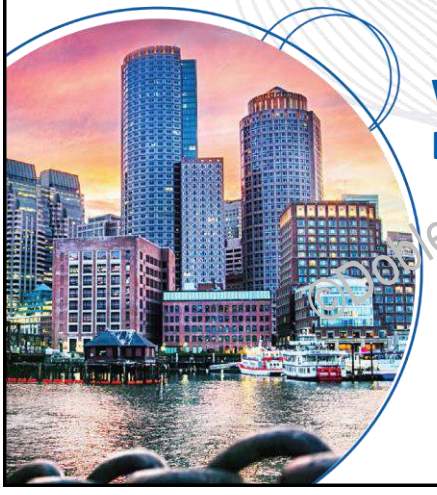

Winding Resistance Issue During Transformer Bushing Replacement

Andrew Stenabaugh – Ontario Power Generation
Ed teNyenhuis – Hitachi Energy

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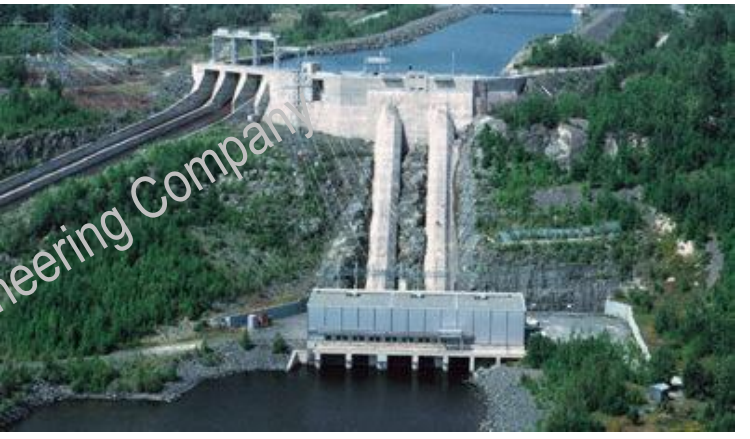
- Site & project background
- Winding Resistance Problem
- Investigation
- Winding Resistance issue modeling
- Conclusions

Ontario Power Generation – Lower Notch GS

- Located on Montreal River (35km from Cobalt, Ontario)
- Into service in 1971

Ontario Power Generation – Lower Notch GS

- Maximum station capacity of 274.2MW
- 2 X 138MVA, 13.8kV generators, G1 and G2
- 2 X 140MVA, 13.4kV-230kV, 3 phase generator step up transformers - T1 and T2



Ontario Power Generation – Lower Notch GS

- Transformers T1 and T2 installed in 2000

Connection to Generator

- LV connection via iso-phase bus duct to generator

Transformer Maintenance

- Yearly - oil analysis, visual inspections of critical components and deluge system testing
- 6 year - complete inspection of tank, bushings, tap changer, lightning arrestors, radiators, gauges, gas relays, auxiliary devices & electrical testing (insulation resistance, power factor, micro-ohm and windings ratio testing on the in-service tap)

LV Bushing Replacement Project

- Repair of leaks on the LV and HV bushing stacks required
- Required replacement of LV bushings, LV bushing gaskets, HV bushing gaskets and some valves
- Project initiated to perform this scope along with complete electrical testing
- Required complete draining of the transformers
- T1 work done in 2021, T2 work done in 2018

Winding Resistance Issue on T1 Unit

- Winding resistance measured before and after the LV bushing replacement – 22% increase in 1 phase and 6% increase in the other 2 phases
- T2 unit had no change in resistance

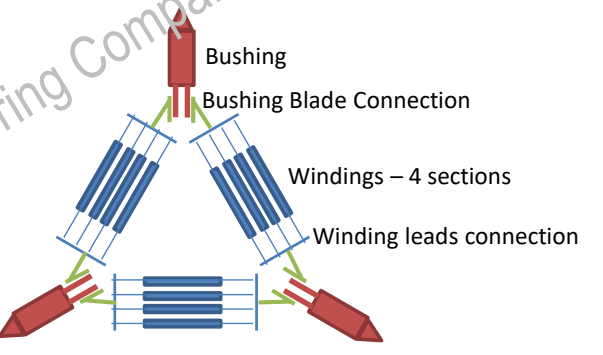
	all milli ohms @85C	X1 - X2	X2 - X3	X3 - X1	% Difference between Phases
1	FAT	2.580	2.580	2.590	0.39%
2	Pre Test	2.554	2.571	2.549	0.87%
3	First Measurement	2.695	3.138	2.681	16.08%
4	% Change	6%	22%	5%	

Measured Winding Resistance Limits

- IEEE Standard C57-152-2013 “IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors”
- Recommended that winding resistance measurements in the field should be within 2% of other phases or the original factory test report, but no more than 5% higher

LV Delta Connection

- LV delta connection made at bushings
- 4 large leads for each winding phase group

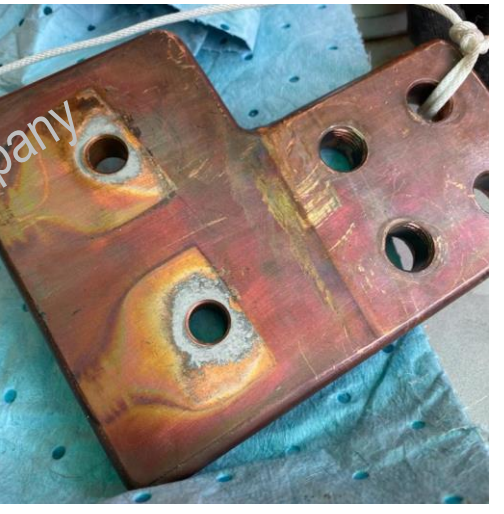


Investigation

1. Remeasured with different test equipment - Same result
2. Measured resistance of bushings only – Very low, not the issue
3. Disconnected bushings and measured without bushings in the circuit – Same result
4. Broke the delta connection and measured each winding phase Measured high result on Winding 2 phase only
5. Measured 4 winding leads on bad phase – OK
6. Disconnected 4 leads at the copper plates - Issue found with the copper plate connecting the winding lead

Investigation Continued

- Found heavy surface contamination or build -up on copper plate
- Removed the copper connector plate and cleaned thoroughly
- Reconnected and winding resistance was good



Copper Plate – Before and After Cleaning

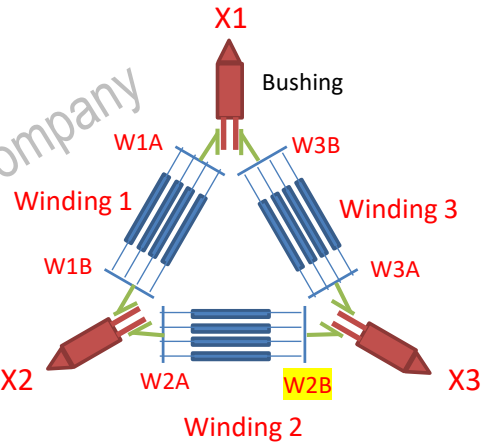
Winding Resistance Measurement

- Final measured values were close to FAT and within IEEE recommended limits

	all milli ohms @85C	X1 - X2	X2 - X3	X3 - X1	% Difference between Phases
1	FAT	2.556	2.586	2.598	0.48%
2	Pre Test	2.554	2.571	2.549	0.87%
3	Final test	2.577	2.683	2.578	4.05%
4	% Change	1%	4%	1%	

Location of Copper Plate Issue – see W2B

- W1A = Winding 1 Top Leads Connection Plate
- W1B = Winding 1 Bottom Leads Connection Plate
- W2A = Winding 2 Top Leads Connection Plate
- W2B = Winding 2 Bottom Leads Connection Plate
- W3A = Winding 3 Top Leads Connection Plate
- W3B = Winding 3 Bottom Leads Connection Plate



Modeling of High Resistance

Normal Case	
All values in milli ohms @85C	
Winding 1 Path	
W1A	0.05
Winding Sections	3.705
W1B	0.05
Total	3.805
Winding 2 Path	
W2A	0.05
Winding Sections	3.705
W2B	0.05
Total	3.805
Winding 3 Path	
W3A	0.05
Winding Sections	3.735
W3B	0.05
Total	3.835

Bad W2B Connection	
All values in milli ohms @85C	
Winding 1 Path	
W1A	0.05
Winding Sections	3.705
W1B	0.05
Total	3.805
Winding 2 Path	
W2A	0.05
Winding Sections	3.705
W2B	1.4
Total	5.155
Winding 3 Path	
W3A	0.05
Winding Sections	3.735
W3B	0.05
Total	3.835

Modeling of High Resistance

X1 - X2 Measurement	
Short path (Winding 1)	3.805
Long path (Winding 2 + Winding 3)	7.64
Bushing X1	0.02
Bushing X2	0.02
Total X1 - X2 calculated	2.580
FAT Measured	2.580

X2 - X3 Measurement	
Short path (Winding 2)	3.805
Long path (Winding 3 + Winding 1)	7.64
Bushing X2	0.02
Bushing X3	0.02
Total X2 - X3 Calculated	2.580
FAT Measured	2.580

X3 - X1 Measurement	
Short path (Winding 3)	3.835
Long path (Winding 1 + Winding 2)	7.61
Bushing X3	0.02
Bushing X1	0.02
Total X3 - X1 Calculated	2.590
FAT Measured	2.590

X1 - X2 Measurement	
Short path (Winding 1)	3.805
Long path (Winding 2 + Winding 3)	8.99
Bushing X1	0.02
Bushing X2	0.02
Total X1 - X2 calculated	2.713
Site Measured	2.695

X2 - X3 Measurement	
Short path (Winding 2)	5.155
Long path (Winding 3 + Winding 1)	7.64
Bushing X2	0.02
Bushing X3	0.02
Total X2 - X3 Calculated	3.118
Site Measured	3.138

X3 - X1 Measurement	
Short path (Winding 3)	3.835
Long path (Winding 1 + Winding 2)	8.96
Bushing X3	0.02
Bushing X1	0.02
Total X3 - X1 Calculated	2.726
Site Measured	2.681

Discussion of High Resistance

- Delta winding resistance connection (bushing to bushing) has 2 paths (short path through 1 winding and longer path through the other 2 windings in series)
- Estimated 1.4 milli-ohms of added resistance at the copper plate (each winding is 3.7 milli-ohms)
- Very large added resistance could be 17kW (I^2R)
- Likely this would have overheated and gassed in service

Discussion of High Resistance

- Problem with copper plate most likely occurred when it was moved slightly to align with the bushing blade
- Slight movement seems to have disturbed the 4 lead connectors on the copper plate
- Corrosion on the copper plate between the connector and the copper plate caused the contact resistance to increase significantly
- Not clear why there was a high contact resistance

Summary / Conclusions

- Even though the bad connection was not part of the bushing changeout, it was disturbed by physical movement
- Calculations later showed the added resistance was in the order of 35% of the winding resistance - would have caused very high loss and heating in this small area if not fixed
- Delta connection made the winding resistance increase appear to be less severe due the parallel phase paths softening the measured phase to phase increase
- Case demonstrates:
  - Importance of the winding resistance measurement
  - Winding resistance differences should be investigated to resolution
  - Subtleties of understanding a high winding resistance in a delta connection