WINDING RESISTANCE ISSUE DURING TRANSFORMER BUSHING REPLACEMENT

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ABSTRACT

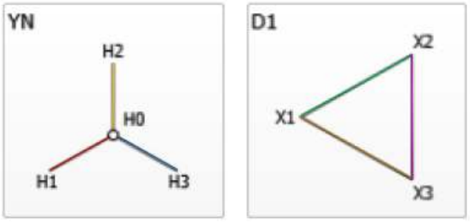
During the replacement of low voltage (LV) bushings on a 140 MVA generator transformer, the measured winding resistance changed significantly. The winding resistance increased by 22% in one phase and 6% in the other two phases (all compared to the original factory acceptance test [FAT]), which is above the recommended IEEE limit of 5% increase. A sister transformer had a similar LV bushing changeout performed earlier with no change in winding resistance. The LV is delta connected with the delta made at the bushing connections. The LV is high current and has 4 large parallel winding leads joined to form the winding phase current and then connected with the leads of another phase to make the delta connection. The high winding resistances were confirmed with different test equipment. Investigations were done as follows: 1) Measure resistance of the bushings only, 2) disconnect the bushings and measure without the bushing in the circuit, 3) break the delta connection and measure each winding phase and, 4) measure each winding lead for all 3 winding phases. Eventually it was determined that the high resistance was caused where the 4 parallel winding leads were joined for one phase. The connection is made on a heavy copper plate by bolted connection, and copper surface corrosion caused a higher contact resistance. Even though this connection was not part of the bushing changeout, the connection was disturbed by physical movement of the copper plate during the bushing lead connection tightening. Once the copper plate and lead connectors were cleaned and everything was reconnected, the measured winding resistances were very close to the original factory acceptance test values. Calculations later showed that the added resistance at the winding lead connection was in the order of 35% of the winding resistance itself, which would have caused very high loss and heating in this small area if not fixed. The delta connection also made the winding resistance increase appear to be less severe due to the parallel phase paths softening the measured phase to phase increase. This case demonstrates the importance of winding resistance measurement, the need to investigate winding resistance differences to resolution and the subtleties of understanding a high winding resistance in a delta connection.

INTRODUCTION

Winding resistance is an important transformer measurement performed routinely on transformers to ensure electrical continuity and to confirm no changes in the current carrying path. During any maintenance or service work done on a transformer that affects the current carrying path, the winding resistance should be measured before all work (to confirm there is no pre-existing issue) and after all work (to confirm the work was done properly). This typically includes bushing replacement, tapchanger maintenance or internal lead repairs. Measured resistances should be compared to previous field measurements and/or to the original factory acceptance test (FAT) report.

IEEE Standard C57-152-2013 “IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors”, recommends 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.

Winding resistance is performed between bushing terminals. For a 3-phase wye connected winding, the resistance measurement includes 2 physical windings—for example see Figure 1 for Yn connection between H1 and H2. For a 3-phase delta connecting winding, the resistance measurement includes 2 parallel paths with 1 physical winding in one path and 2 physical windings in series in the second path—see Figure 1 for delta connection between X1 and X2. As will become clear later in the paper, the issue in a particular winding leading to a measured increase in winding resistance can appear to be a smaller problem then it really is.



Wye and Delta Connection
Figure 1

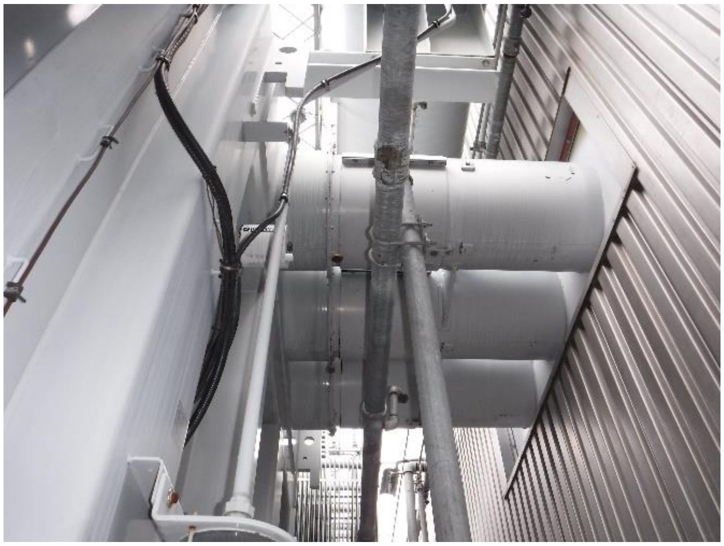
PROJECT BACKGROUND

Lower Notch hydro-electric generating station is owned and operated by Ontario Power Generation and is located on the Montreal River, 35km from the town of North Cobalt in Northern Ontario, Canada. The facility was placed in service in 1971 and has a maximum station capacity of 274.2MW. The station includes two 138MVA, 13.8kV generators, G1 and G2. The voltage is stepped up to 230kV via two 140MVA, 13.4kV-230kV, 3 phase generator step up transformers, T1 and T2. See Figure 2 to Figure 4. The transformers are connected to their corresponding generators through 13.8kV insulated phase bus duct as seen in Figure 5.

Lower Notch Generating Station
Figure 2

Transformer T1
Figure 3

Transformer T2
Figure 4



Insulated Phase Bus Duct
Figure 5

Both transformers T1 and T2 were manufactured by ABB in 1999 and installed in 2000. Yearly maintenance performed on both transformers includes oil analysis, visual inspections of critical components and deluge system testing. The six-year maintenance routine includes a complete inspection of the transformer tank, bushings, tap changer, lightning arrestors, radiators, gauges, gas relays, auxiliary devices along with insulation resistance, power factor, micro-ohm and windings ratio testing on the in-service tap.

Both transformers developed minor oil leaks which appeared to be originating at the mounting bases of the high voltage and low voltage bushings. OPG engaged ABB/Hitachi to complete an inspection of both transformers. From their inspection, ABB/Hitachi determined that the low voltage bushings and gaskets required replacement along with the high voltage bushing gaskets and some ball valves. OPG opened a project to repair the transformers. The scope of the project included replacement of the low voltage bushings, high voltage bushing gaskets, replacement of leaking ball valves and other leaking gaskets along with complete electrical testing of the transformer once the work was complete. The project was completed on Transformer T2 in 2018 and on Transformer T1 in 2021.

WINDING RESISTANCE PROBLEM

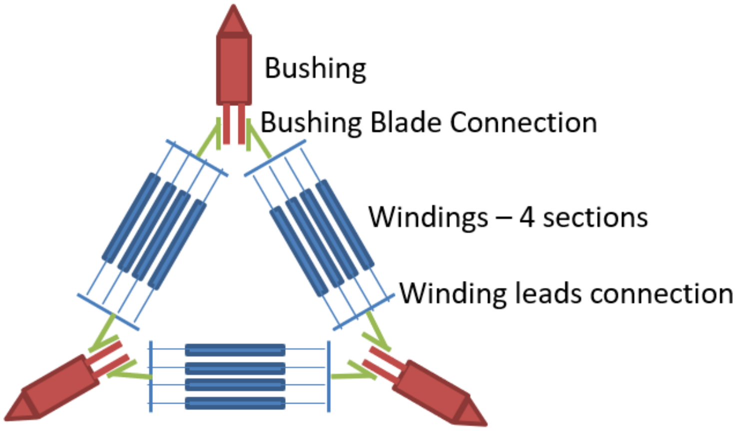
The winding resistance of the LV was measured prior to all work and it agreed very closely with the FAT measurements. This is shown in Rows 1 and 2 of Table 1. The phase values are within 0.39% for the FAT measurements and 0.87% for the Pre-Test measurements.

Table 1
Measured Winding Resistances

	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%	

The LV bushings were then replaced, and the LV winding resistance was measured, as shown in Row 3 of Table 1. These measurements differ by 16% between phases and by 5 – 22% from the Pre-Test measurements, which was not acceptable. The X2 – X3 measurement value is 22% higher than the Pre-Test while X1 – X2 and X3 – X1 are 5 – 6% higher than the Pre-Test value.

The bushing-to-bushing winding resistance measurement is shown below in Figure 6. The delta connection is made at the bushings. There are 4 winding leads (4 parallel winding sections) due to the high current of the LV. The 4 winding leads are connected to a copper plate and the copper plate connects to one blade of the bushing. The other bushing blade has a copper plate connecting 4 winding leads from another winding. A picture of the connections at the bushing is shown in Figure 7.



Sketch of the Internal Winding and Lead Connections for the Delta Connection
Figure 6

Winding Leads Connected to the Copper Plate at the Bushing
Figure 7

WINDING RESISTANCE INVESTIGATION

The winding resistance issue was investigated in the following systematic manner:

1. Remeasured with different test equipment—The same test result was achieved so the test setup and test equipment were not the issue.
2. Measured resistance of bushings only—All the LV bushings had very low resistances, namely a few micro-ohms or 1/1000 of the measured winding resistance. Thus, there was no issue with the bushings.
3. Disconnected the bushings and measured without the bushings in the circuit, since the copper plates were connected to make the delta—The measured winding resistances were unchanged.
4. Broke the delta connection and measured each winding phase separately—One of the windings measured much higher than the other 2 windings.
5. Measured each of the 4 winding leads on the “bad” winding—Each of the winding leads was found to have similar resistance. In fact, when the 4 measured winding resistances were calculated in parallel, this was very close to the measured resistances of the other 2 winding phases. Thus, the issue had to be with the connection of the 4 winding leads to one of the copper plates.
6. Winding leads were disconnected from the 2 copper plates—The issue was seen on one of the copper plates where there was heavy surface corrosion or surface coating between the copper plate and the winding leads. The copper plate was removed from the transformer and thoroughly cleaned (see Figure 8).
7. Reconnected the winding leads to the cleaned copper plate—The winding phase was remeasured, and the value was close to the other phases.
8. Everything was fully reconnected—The winding resistances between LV bushings was measured and found to be close to the Pre-Test and FAT. See Table 2 for the final measured values compared to FAT and pre-test.

Table 2
Final Measured Values Compared to FAT and Pre-Test

	all milli ohms @85C	X1 - X2	X2 - X3	X3 - X1	% Difference between Phases
1	FAT	2.586	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%	

Copper Connection Plate (Before and After Cleaning)
Figure 8

In order to understand the copper connection plate problem, the resistances of the various winding, connections and bushings were modeled in Table 3 and Figure 9. Each winding was called a "winding path" which includes the actual winding sections and the connection of the 4 winding leads onto the copper plate. For example, "Winding 1 Path" is the sum of W1A, W1B and the winding itself for a total of 3.805 milli ohms. The measured winding resistance between 2 bushings includes the parallel sum of 2 paths – a short path through 1 winding and a longer path through the other 2 windings in series. For example, the measurement of X1 – X2 is the parallel sum of Winding 1 and (Winding 2 + Winding 3). The resistance values of the bushings and the copper plate connections was assumed to be very low and the winding sections resistance was selected so the X1 – X2, X2 – X3 and X3 – X1 calculated values matched the FAT. This is all shown in the left column of Table 3.

The problem was found to be in the W2B connection location. The resistance of this W2B connection had to be increased signficantly in order for the X1 – X2, X2 – X3 and X3 – X1 calculated values to match the measured Pre-Test values (it is not exact but very close).

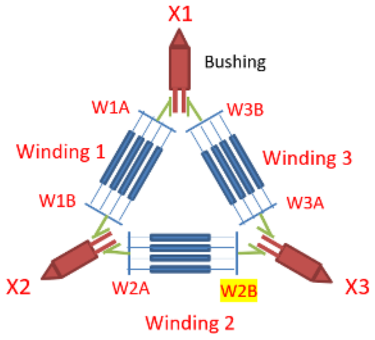
The estimated 1.4 milli-ohms at the W2B connection is about 1/3 of the winding resistance, which is significant. This could lead to an estimated 17kW increase in load loss due to the high LV current and most likely a very high temperature increase at this location.

Table 3
Estimation of the Contact Resistance Increase

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
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

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
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

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



Identification of Winding and Leads for Table 2
Figure 9

DISCUSSION

The problem with the copper connection plate most likely occurred when the heavy plate was moved slightly to rearrange its position to match the bolting to the new bushing. Although the new bushing was designed to be a direct replacement, the copper plate had to be disturbed to push it into position. This slight movement seems to have disturbed the 4 lead connectors on the copper plate. The corrosion on the copper plate between the connector and the copper plate caused the contact resistance to increase significantly. It is not clear why there was a surface issue on this one particular copper plate and not on the other copper plates.

The calculated 1.4 milli-ohm contact resistance, if left in place, would have likely overheated and caused gassing. It was thus prudent that the investigation and repair was performed.

The delta connection does lessen the apparent measured resistance increase of a high resistance in one winding phase. This of course is due to having two paths for the resistance measurement for each bushing-to-bushing resistance measurement. A doubling of the resistance in one winding phase gives only a 50% increase in measured winding resistance (bushing-to-bushing). Thus, it should be kept in mind that a high measured winding resistance in a delta connection might be up to double the increase for one of the windings.

It is very important to measure winding resistance during bushing replacements and it is recommended to perform a quick measurement right after the bushing replacement is complete (and before oil filling if the oil was removed). If there is an issue it is easier to investigate while all equipment is in place. The final reported winding resistance can be performed during all the final electrical testing which is typically done after all work is complete.

This case also demonstrates the importance of investigating any discrepancies in measured winding resistance that exceed the tolerances in industry standards.

CONCLUSIONS

A high measured winding resistance case and the investigation of it was presented. The issue was found to be with the contact resistance of winding lead connectors to a copper plate. 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 and it would have likely caused increased loss, overheating and gassing in oil if not fixed.

The transformer delta connection made the winding resistance increase appear to be less severe due to parallel phase paths (for the resistance measurement) which softens the measured phase to phase increase.

This case demonstrates the importance of the winding resistance measurement and the necessity of investigating winding resistance differences to resolution.

The subtleties of understanding a high winding resistance in a delta connection were also presented.

ACKNOWLEDGEMENTS

The authors want to acknowledge James McFaul of Hitachi Energy for the site investigation and electrical test results.

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[1] *IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors*, IEEE Standard C57-152-2013, 2013.

BIOGRAPHY

Andrew Stenabaugh is a Senior Plant Engineer at Ontario Power Generation's Northeast Operations and has been employed at Ontario Power Generation since 2016. Andrew received his B.A.Sc. in Electrical Engineering from Lakehead University in Canada and is a Professional Engineer in the province of Ontario.

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