CATASTROPHIC FAILURE OF AN ASEA TYPE IMBE-170 A4 CURRENT TRANSFORMER

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ABSTRACT

An explosion of a current transformer (CT) was observed in a 161kV electrical substation. The failure projected pieces of porcelain more than 250 feet and caused a fire on the equipment. The CT was built in 1988 and operated and tested without any issue until failure. This CT was installed in a substation supplying industrial loads, including aluminum potlines that generated harmonic currents. The harmonic filter had been taken out of service for seven days before this failure. An autopsy was performed on the failed CT and two adjacent CTs installed in the other phases. The source of the defect was identified but the fundamental cause was still unknown. Insulation measurement and oil samples were carried out on all similar models in all our stations. A replacement program was implemented and prioritized based on the measurement campaign.

INTRODUCTION

Measurement of the CT insulation quality, a.k.a. power factor (PF) test, is essential in condition monitoring for the safety and reliability of electrical substations. Typically, the test is performed during a planned outage and routine maintenance of the substation apparatuses, which has an interval of six to eight years. No oil samples are taken on this equipment because it is complex to remove oil in small volumes without risking contamination of the equipment. Therefore, the asset management is mainly based on the condition of its electrical insulation, a visual inspection and thermal inspection.

Three identical single-phase CTs were installed in a 161kV network to feed industrial loads including a potline of aluminum electrolysis, and their nameplate and identification are provided in Table 1 and 2. A harmonic filter is present in the same network to eliminate harmonics. However, a few weeks before the failure, the filter had been taken out of service for maintenance reasons. A remaining question is whether an increase in the harmonic level or resonance phenomena have affected the electrical insulation of the CT.

Table 1
CT Nameplate

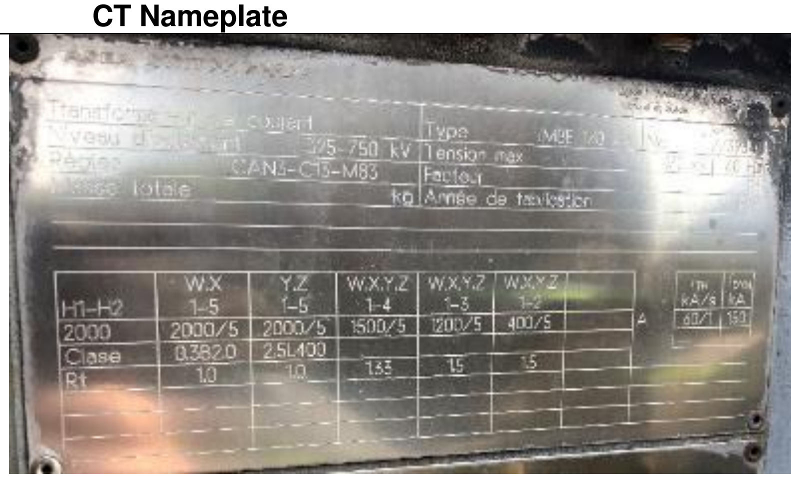
ABB **Made in 1988 by Sweden** **Type: IMBE 170 A4** **Serial number : 7739541** **Rated voltage : 170 kV** **Standard : CAN3-C13-M83** **4 secondary windings** **Shed porcelain insulator**	

Table 2
CT Information of Group 1

Phase	Serial number	Equipment number
A	7739539	T6111
B	7739540	T6112
C (failed)	7739541	T6113

DESCRIPTION OF FAILURE EVENT

On July 6, 2023, a loud noise was heard in the high voltage substation in Figure 1a and a fire was observed on the phase C, in Figure 1c. Multiple pieces of porcelain were found over 250 feet around the CT and some pieces had damaged a nearby power transformer and the circuit breaker. Additionally, a piece of porcelain was found in a neighboring garage in Figure 1b.

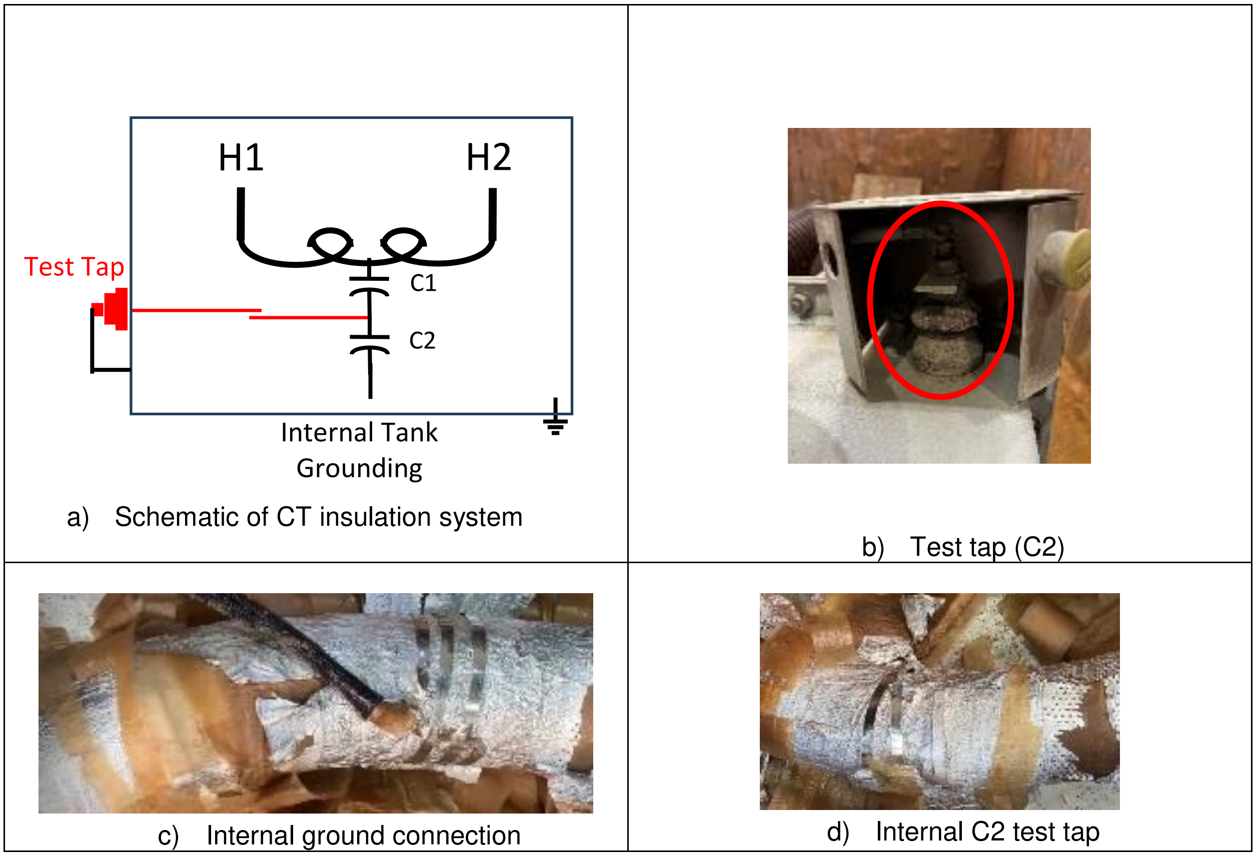
a) Failed CT in 161kV substation

b) Flying porcelain in nearby garage wall

c) Failed CT on fire and damage

Overview of the Failed CT in Phase C
Figure 1

Each CT is composed of a measurement tap (C2) that is connected to ground in normal operation (Figure 2b) and another measurement system that is the main insulation (C1) of the CT. The insulation system between the ground and the test tap consists of only a few layers of insulating paper (Figure 2c). This small insulation system measurement should be able to detect earlier internal degradation like oil contamination.



a) Schematic of CT insulation system

b) Test tap (C2)

c) Internal ground connection

d) Internal C2 test tap

Overview of the CT Insulation System
Figure 2

FAILURE INVESTIGATION

Maintenance History

The insulation measurement was performed routinely every six years on this 161kV instrument transformer. The last test was dated in 2017 and consisted of an overall test at 10kV and 2kV for monitoring the power factor tip-up. However, the C2 measurement had been abandoned because of a complication in selecting a correct test voltage for field testers. Furthermore, some C2 tests were done at 10kV, which risked damaging the tap insulation. Table 3 and 4 show the last test results and the history of the overall test. No significant data change was observed from 2006 to 2017 and the PF in the latest test (2017) was within acceptable limit before the CT failed in 2023.

Table 3
Results of the Last Test PH C CT in 2017 Before Failure

Setup						Results							Ratings		
#	H1	H2	Tap	Insulation System	Test kV	V [kV]	I [mA]	Loss [W]	TCF [#]	PF [%]	PF*TCF [%]	Capacitance [pF]	Ask FRANK™		Manual
1	HV			CH	10.000	10.001	3.597	0.091	1.00	0.252	0.252	954.2	Good	...	Unrated
2				CH	2.000	2.000	3.598	0.093	1.00	0.257	0.257	954.6			Unrated
3			Red LV Lead	C1	10.000	10.001	*	*	*	*	*	*	Unrated	...	Unrated
4	Red LV Lead		HV	C2	10.000	10.002	*	*	*	*	*	*	Unrated	...	Unrated

Table 4
History of Overall CH at 10kV

Date	Power factor (%PF)			Capacitance (pF)		
	PH A	PH B	PH C	PH A	PH B	PH C
7/10/2023	0.28	0.22	Failed	848	1016	Failed
10/12/2017	0.32	0.26	0.25	846	1008	954
8/29/2012	0.29	0.23	0.22	829	999	943
9/20/2006	0.51	0.41	0.40	829	998	941

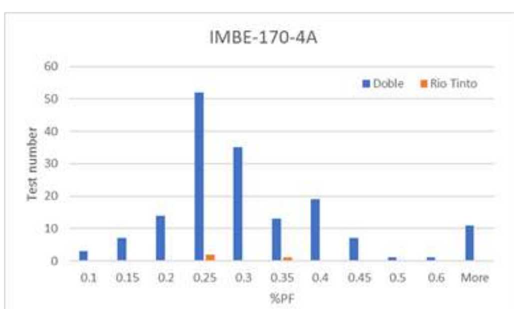
Electrical Tests

To help the investigation of the failed CT, the two sister units were used as benchmarks to determine the CT insulation conditions by testing then autopsies. Testing consisted of the overall power factor (PF), variable frequency power factor (VFPF), and sweep frequency response analysis (SFRA).

PF Tests: The PF tests were performed on July 10, 2023 and provided the results in Table 5. The measured PFs were all within the acceptable limits and statistically well below the data from the previous test in Figure 3. The three CTs have noticeably different capacitances from each other; the deviation varies from 5% to 18%, suggesting some variation in the CT construction. However, the measured capacitance remained stable, with slight increases but still below 2% when compared to their baseline capacitance in 2006. All capacitance measurements are slightly different between the CTs, which can be explained by small differences in their construction.

Table 5
PF Test Results

	PH A (7/10/2023)		PH B (7/10/2023)		PH C (2017) before failure	
	%PF	Cap (pF)	%PF	Cap (pF)	%PF	Cap (pF)
Overall **10kV**	0.220%	848.3	0.276%	1016.0	0.252	954.2
Overall 2kV	0.226%	848.8	0.282%	1016.6	0.257	954.6
C1	0.193%	767.6	0.247%	931.4	Not Performed	
C2 (2kV)	0.213%	19670	0.243%	23744.0		

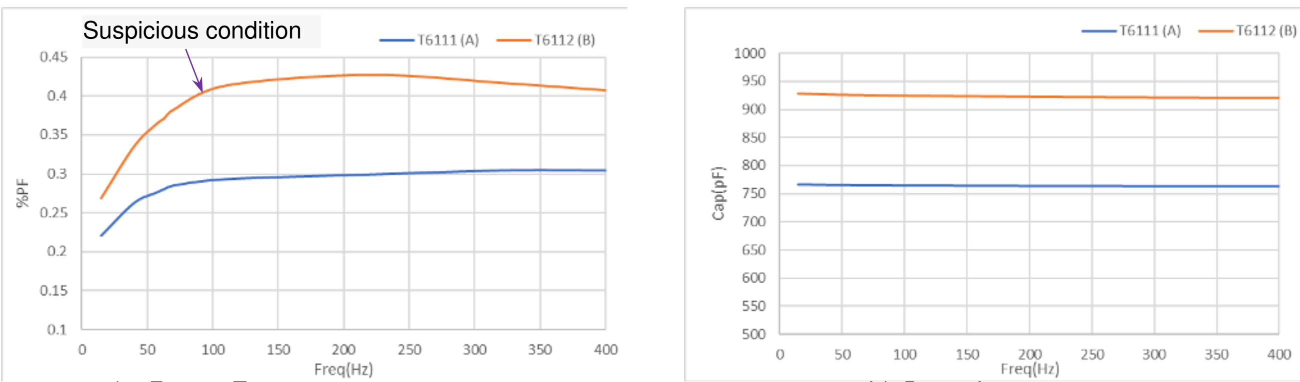


Doble Reference Overall Power Factor Since 2006-2023
Figure 3

VFPF Tests: Figure 4 describes the VFPF C1 test configuration on the sister units: test voltage at 2 kV, frequencies sweeping from 15 to 400Hz. The results are plotted in Figure 5 and 6 and correlated with the overall test data in Table 5. At power frequency (60Hz), the VFPF detected the same pattern of capacitance and PF as measured by the overall tests, so the observations mentioned in the previous section of overall test apply to VFPF as well. The capacitance remained stable across the frequency spectrum. The PF versus frequency was lowest at 15Hz, then rose to form a shape of an inverse “fish-hook,” typically caused by low conductive losses in the insulation. But when comparing the two traces in Figure 5a for C1 or in Figure 6a for C2, it is remarkable that the higher the power factor, the greater the shape of the inverted fish-hook. This behavior was identified as Pattern 4 in [1], making the PH B condition suspicious.

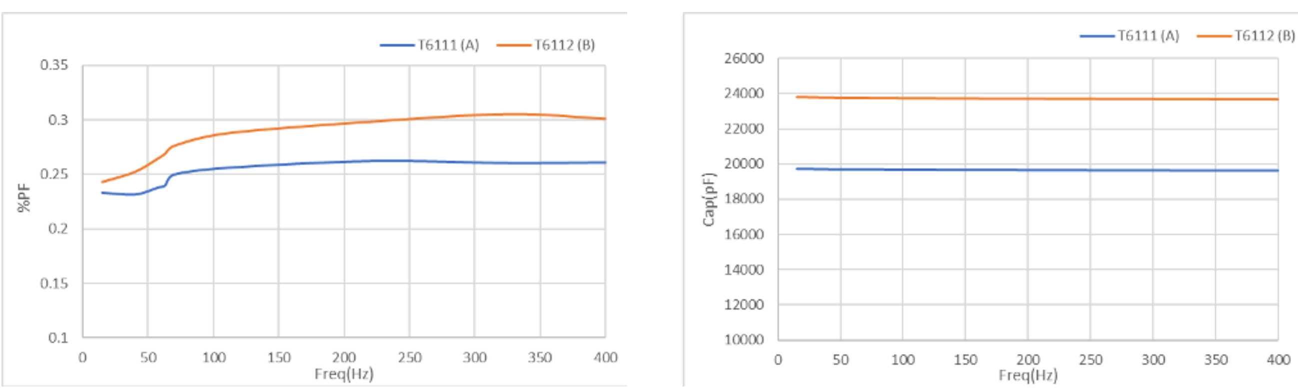
Setup								Results	
#	Center Conductor	Tap	Insulation System	Voltage [kV]	Start [Hz]	Stop [Hz]		Temperature	Test Completed
1	HV	Red LV Lead	C1	2.000	400	15	...	22.8 °C	✔
2	Red LV Lead	HV	C2	2.000	400	15	...	22.8 °C	✔

VFPF Test Setup Voltages and Frequency
Figure 4



a) Power Factor b) Capacitance

C1 VFPF Test Results of 2 Other Units
Figure 5



a) Power Factor b) Capacitance

C2 VFPF Test Results of 2 Other Units
Figure 6

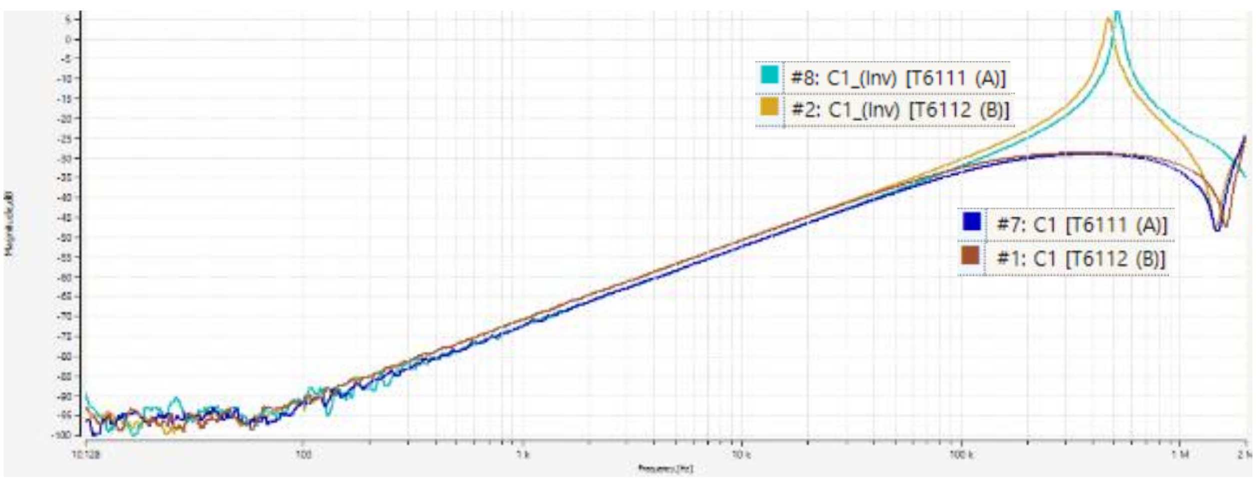
SFRA Tests: Figure 7 describes the SFRA test configuration: C1 test and open-circuit tests are identified by Iex on each secondary winding of both sister CTs with the frequencies sweeping from 10 Hz to 2 MHz. The graphical results are provided in Figures 8 and 9, which detected the same pattern of capacitance measured in the overall tests, i.e. PH B has higher capacitance, hence higher dB responses than PH A.

Custom Test Plan

	Setup							Results	
		Preferred						Traces	
#	Test Identification	Start Freq. [Hz]	Stop Freq. [Hz]	Red Lead	Black Lead	Shorted	Grounded	#	Test Completed
1	C1	10	2 M	H1	S0L0	none	none	1	✓
2	C1_(Inv)	10	2 M	S0L0	H1	none	none	1	✓
3	W_Iex	10	2 M	W	w	none	none	1	✓
4	X_Iex	10	2 M	X1	X0	none	none	1	✓
5	Y_Iex	10	2 M	Y1	Y0	none	none	1	✓
6	Z_Iex	10	2 M	Z1	Z0	none	none	1	✓

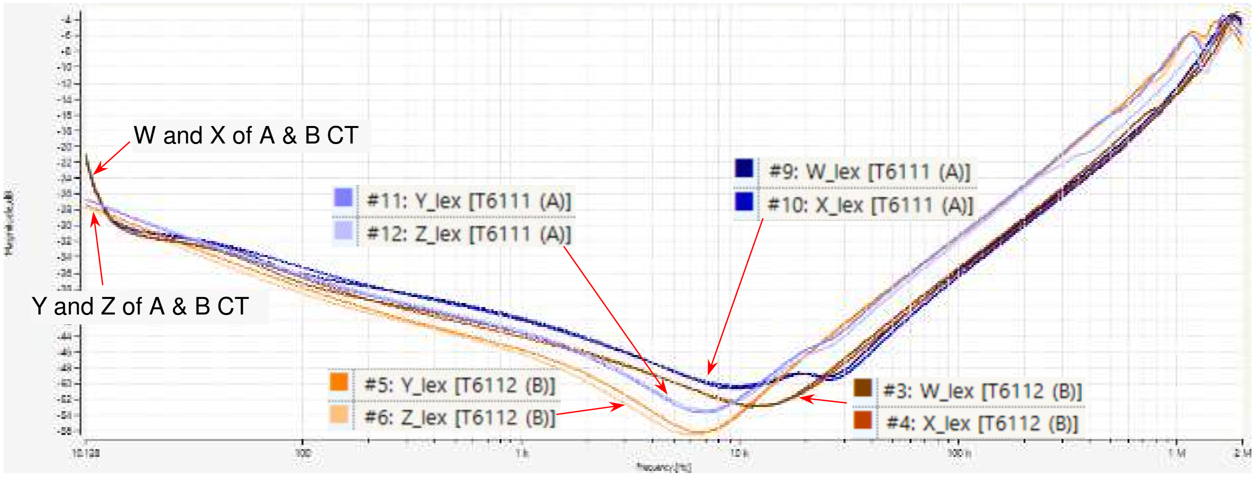
SFRA Configuration for Testing Sister Units
Figure 7

The C1 traces in Figure 8 exhibit comparable frequency characteristics between the PH A and B CTs, meaning similar shapes and different resonance frequency due to the dissimilarity of their capacitances. However, the C1 (Inv) trace behaves differently from the C1 trace regarding the resonance type, the former has series type resonance (peak), and the latter has parallel type resonance (valley). This was probably caused by the CT magnetization reactance being excited in C1 test and not excited in C1 (Inv) test.



SFRA Tests on C1 - T6111 (A) Versus T6112 (B)
Figure 8

The traces of the open-circuit tests (Iex) in Figure 9 classified the four secondary windings into two groups: W&X and Y&Z, suggesting that the four windings were regrouped into two winding structures and this difference was confirmed by the CT nameplate, which shows two different classes, 0.3B2.0 for W&X windings and 2.5L400 for Y&Z windings.



SFRA Tests on Secondary Windings (W, X, Y & Z) - T6111 (A) Versus T6112 (B)
Figure 9

Oil Test Results

During the replacement of the three current transformers, oil samples were taken to the laboratory to test the dissolved gas in oil and its quality, and the results are summarized in Table 6. The oil from the two sister CTs had high hydrogen and low dielectric breakdown, according to IEC 60599-2015. Furthermore, the PH B CT appeared to have contaminants in oil that caused a higher power factor of 100°C. This contamination issue could have occurred in the oil of the failed C CT because its 100°C power factor was very high; however, this could also be the result of the violent failure.

Table 6
Oil Results in PPM (Sampled at Repair Shop on the Floor)

Test	PH A	PH B	PH C (fired)
H2	**1644**	**1010**	18365
CH4	6	5	6268
C2H6	1		1256
C2H4	4	3	2740
C2H2			1237
CO	180	157	860
CO2	605	610	4130
N2	71274	68964	43674
O2	9813	14080	7901
PPM H2O	20	**22**	15
IFT	41.58	39.54	39.72
ACID	0.008	0.010	0.003
KV, D1816-2mm	**25 KV**	**19 KV**	33 KV
PF 25degC	0.085%	0.446%	1.226%
PF 100degC	2.2312%	**11.764%**	18.537%
Furans (2FAL)			1715

This failure triggered a campaign of oil sampling and electrical testing on all the CTs with the same type (IMBE-170). Thirteen current transformers were counted in Rio Tinto network and tested with the results summarized in Table 7. All CTs have a relatively high hydrogen (H2) content exceeding the limit of 300 ppm for hydrogen (H2) by IEC 60599-2015 standard, but they passed the overall insulation test with the C1 %PF well below the limit of 0.5%, including the C2 test, which is not included in the Table.

Table 7
Other Similar Unit by Serial Number, Oil Result in PPM and PF %

S/N	712881	7867497	7739544	7128884	7128883	7128882	7739542	7739543	6691483	6691481	6691482	7364160	7364161
H2	666	460	528	915	1205	1183	507	396	805	1037	693	621	856
CH4	6	12	6	9	7	7	8	7	6	6	7	7	5
C2H6	1	2	2	3	2	1	1	1	2	2	2	1	1
C2H4		12		1	1	1	3	3			3	8	6
C2H2													
CO	168	427	201	226	185	216	247	222	81	110	259	338	302
CO2	339	850	497	577	437	616	713	586	190	210	431	1110	1052
N2	44633	64617	75847	49267	45764	114220	69419	79014	56449	49625	61143	77167	77582
O2	2715	1409	1605	1814	1061	19135	1826	1936	2239	1252	1206	3892	4600
H2O	7	6	7	7	6	6	9	11	10	9	7	9	10
C1 %PF @10kV	0.249	0.390	0.259	0.225	0.126	0.160	0.275	0.263	0.175	0.164	0.166	0.175	0.176
2kV %	0.259	0.407	0.268	0.174	0.131	0.154	0.288	0.273	0.183	0.173	0.172	0.184	0.184

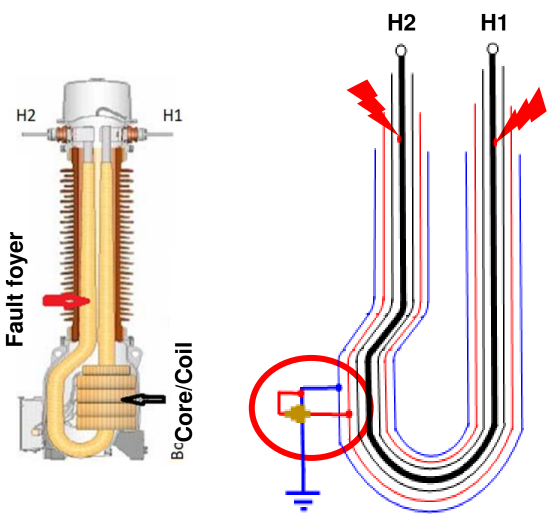
Teardown and Inspection

All three current transformers in the failed CT Group were brought to the shop and torn down to collect evidence for determining the root causes of the failure and to understand the failure mode for preventing the failure from happening with other units. The failed PH C CT had no housing insulator due to the explosion exposing the primary HV conductor linking between the head and the base tank, as shown in Figure 10a. The external inspection revealed that the head section was in good condition and the damage was concentrated from near mid-section down to the test tap. There was an arcing spot on each primary conductor pointed by the red lightning bolt in Figure 10a and 10d. This meant that the arc punched through all conductive layers of the C1 insulation from the primary conductor, tracked to the conductive layer of the test tap and discharged downward to the grounded test tap at the bottom of the base tank. As a result, the leads on the test tap and the secondary terminals were partially melted and were blown out of the tank, as shown in Figure 10b. Furthermore, the disposition of the arcing spots suggested an occurrence of arc-over between the two stems of primary conductor before finding the grounded layer of the test tap to be discharged.

The CTs in the other two phases were in good condition and dismantled to study the insulation system in hopes of detecting any weakness or signs of deterioration. After removing the head and the housing insulator, the insulation system in Figure 11a was in excellent condition, including the core/coils, leads of the C2 ground, test tap and secondary, as shown in Figure 11b. Due to time constraints, the insulating wraps were cut to the conductor at once instead of removing each individual layer, and then they were visually inspected without finding any abnormality.

a) External failed CT, secondary terminals and test tap

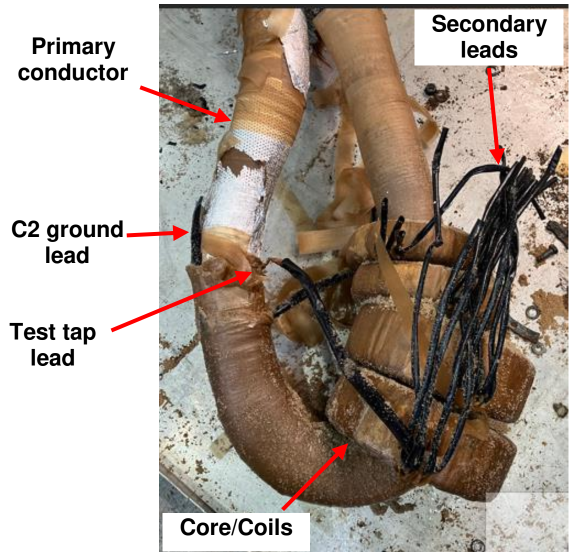
b) Tank, galvanized steel and damage



c) fault localisation schematic

d) picture fault localisation

Failed CT in Phase C
Figure 9

	
a) Primary HV conductor, core & coils of secondary in the tank	b) Test tap, C2 ground and core & secondary coils

Condition of CT in A and B Phases
Figure 10

CONCLUSIONS

Any catastrophic failure is a very concerning event because it can impact the personnel safety and the reliability of the electrical substation. Maintenance and inspection are important measures to manage this concern to an acceptable level; in spite of the "overall" isolation tests performed during maintenance with six-year intervals, the deterioration of the CT insulation had not been detected in time to prevent this failure. However, this investigation provided some evidence of the failure modes, avenues for improvement for our testing program and implementation of a replacement program.

The failure mode seemed to be nonprogressive, meaning it developed in a short period before failure, and therefore it was difficult for it to be detected by the six-year testing interval. The VFPF and oil tests revealed that the PH B CT had suspect characteristics, which could have been a sign of condition change, unfortunately the autopsy did not corroborate this. Another common issue in these CTs was high levels of Hydrogen (H2), the cause of which is still unknown. However, it seems to occur often in an instrument transformer, and even in new units. Currently, this gassing condition does not appear to affect the insulation test results or the main insulation presently. Given the complexity of taking oil samples, including adding oil afterward, and our limited technical skill and field staff, this technique is reserved only for diagnostics test, when CT models had failed in our substation.

Following the failure and investigation, a replacement program of IMBE-170 current transformers was established, and the priority was based on the insulation measurements, oil analyses and criticality of the load and location.

Two remaining questions are whether the absence of harmonic filter could be the cause and if the C2 test would help to detect an early developing defect in the fluid before affecting the C1 insulation. To this end, we will reinstate the C2 test in our test program, which is supported by establishing training for field testers. However, we did not investigate the former question about the effect of harmonic filter.

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BIOGRAPHY

Hugo Simard, P.E., works as electrical engineer for Rio Tinto Aluminum in strategic expertise group, and has amassed over 28 years of experience in asset management on transformer, hydroelectric generator, and aluminum rectifier substations. He is an active participant in the Doble community and Chairman of the Rotating Machinery committee, and has published numerous technical papers. He is an IEEE member, a registered professional engineer in Quebec, and he obtained a Bachelor's from the University of Québec in Chicoutimi, Canada, in 1997.

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