

Analysis of Converter Transformer Failures and Application of Periodic On-line Partial Discharge Measurements

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Abstract: Of a group of eight 3-phase core form HVDC converter transformers, six have now failed in service. The final failure mechanism has consisted of a turn-to-turn fault, usually in the valve winding. All the windings were produced using continuously transposed conductors. Thermal aging of the insulating materials was evident. This paper summarizes the results of the various tests and inspections that were made in an attempt to better understand the circumstances that may have contributed to these failures.

On-line partial discharge measurements using an electrical detection method are being made on a periodic basis on a number of large power transformers, primarily those used in HVDC conversion. This paper describes the measuring system and methods of noise deletion. An example of the test results has been provided describing a significant failure hazard that was detected.

INTRODUCTION

The first stage of the Nelson River Bipole 2 HVDC transmission consists of one 250 kV 500 MW 12 pulse valve group per pole. Each valve group originally had two 3-phase core form converter transformers rated 279 MVA at the rectifier and 262 MVA at the inverter. The line winding is connected 230 kV grounded star. The valve windings were originally rated 109.7 kV at the rectifier and 103.1 kV at the inverter. The valve windings of one transformer are connected in delta and are insulated for 125 kVdc with respect to ground. The valve windings of the second transformer are connected in ungrounded star and are insulated for 250 kVdc with respect to ground.

The core of each of the original transformers has three vertical limbs. The position of the windings on the core is: valve → line → tap → core. The tap winding is in series with the line winding. The on-load tap changer has 27 positions, with 13 either side of neutral.

The transformers are directed oil cooled and are equipped with fans (ODAF). These transformers do not have a self-cooled rating.

EARLY TRANSFORMER EXPERIENCE

These transformers were first placed in service in 1978, and by late that year or early in 1979 two of the eight transformers

(one at the inverter and one at the rectifier) had experienced significant gassing problems. Both were returned to the factory in 1979. In the case of the transformer from the inverter, the cause of the gassing was found to be as a result of a piece of steel banding that had been left around the top yoke of the core.

In the case of the transformer from the rectifier, the cause of the gassing was more complex. The tap leads are arranged in parallel with the top and bottom yokes of the core as is shown in Figure 1 and are connected at the tap changer so as to place in series the individual tap windings. As all the tap leads at the top yoke have one polarity, while those at the bottom yoke have the opposite polarity, there is considerable net stray flux when the transformer is operating on an extreme tap. This resulted in eddy current heating of the adjacent core laminations (Figure 2), and possibly also eddy current heating of the adjacent winding conductors. As the transformers at the rectifier tend to operate closer to an extreme tap, continuous aluminum shields were placed on the top and bottom yokes of the core on the side closer to the tap leads. These shields were connected between top and bottom at each end of the core so as to provide a continuous shield with the intention of reducing the stray flux heating of the core. At first the continuous shield was provided only for the one gassing transformer from the rectifier. After about 14 years of operation, two additional transformers, having evidence of gassing, were returned from the rectifier to the factory and the continuous shield was installed.

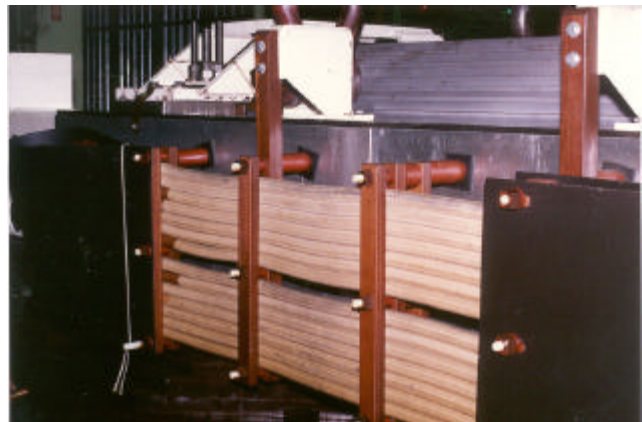


Fig. 1 Location of tap leads at top yoke of core

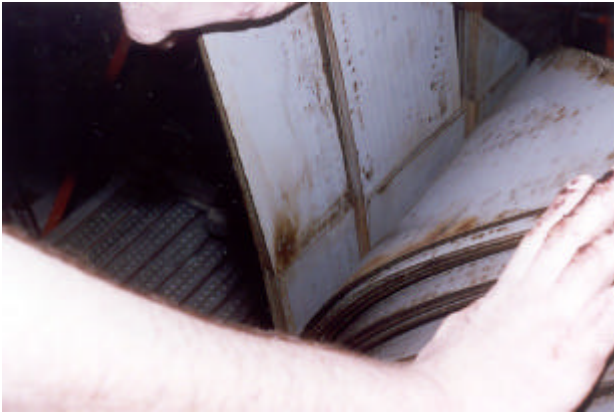


Fig. 2 Evidence of overheating of outer laminations of vertical limb adjacent to top yoke of core after approximately 14 years of operation

From 1979 until additional HVDC conversion was added in 1983/84 the transformers operated at close to full load. Thereafter the transformers operated at a lower load until 1990/92 when additional generation was placed in service.

During internal inspections in 1988, after about ten years of service, it was common to find the rubber oil seal dislodged between the discharge from the oil circulation pumps and the bottom core clamping structure from which the oil was forced through the coil assembly. An improved oil seal was installed. It was also observed on these occasions that the laminations of the top yoke of the core were relatively loose and in some cases shifted laminations were found. It was common to find evidence of overheating at the mitre joints at the top yoke of the core.

IN-SERVICE FAILURES

One of the eight converter transformers that had been first installed in 1978 failed in service in 1994 and by the end of 2000 a total of six had failed. A summary of the six failures will be found in Table I.

Table I
Bipole 2 Stage 1 Converter Transformer Failures

Date of Failure	Location/ Connected	Winding/ Position	Leg	Protection
1994 02 21	Inverter/ Star	Valve/ Top	3	Gas alarm → manual trip
1998 05 06	Rectifier/ Star	Line/ Top	2	Ground differential
1998 08 26	Rectifier/ Delta	Valve/ Bottom	3	Pressure relief
1999 11 06	Inverter/ Delta	Valve/ Top	2	Pressure relief
2000 02 14	Inverter/ Star	Valve/ Top?	2	Sudden pressure (fast gas)
2000 09 22	Rectifier/ Delta	Valve	1	Gas alarm → Pressure relief

Information on the individual failures is as follows:

February 1994 Failure

Analysis of free and dissolved fault gases indicated circulating currents and/or hot joints with possible cellulose overheating. Following the fault, 45 ppb of furfuraldehyde and no furfuryl alcohol were found in the oil. These values were virtually unchanged from the condition 11 months earlier.

The first turn of the first disc of the valve winding at the top of Leg 3 was found to have burned open circuit immediately adjacent to the static ring. This star connected valve winding has two continuously transposed conductor (CTC) bundles in parallel with 23 strands each.

In 1983, a ball bearing equipped oil circulation pump had failed and contact of the impeller with the housing had contaminated the core and coils with both aluminum and iron particles. Cleaning was not attempted until 1988.

May 1998 Failure

Analysis of free and dissolved fault gases indicated circulating currents and/or hot joints with cellulose overheating. Following the fault, 415 ppb of furfuraldehyde and 10 ppb furfuryl alcohol were found in the oil whereas in 1996, only 40 ppb of furfuraldehyde had been detected.

Shorted and open circuited turns were found in the top disc of the line winding at the top of Leg 2 immediately adjacent to the static ring. A flashover had occurred from this point through the pressboard barriers to the valve winding and thence to ground by way of the thyristor valves and the earth electrode line.

The star connected valve winding has two bundles of 11 strands and two bundles of 12 strands. During salvage of the transformer, the coils on the unfaulted legs were examined. It was found that three strands were shorted in one bundle on Leg 3.

The paper wrap on the strand bundles was checked in manual tension. None of the paper samples taken from the bottom of the coils would break. All of the paper samples taken from the top of the coils would easily break in manual tension, with the exception for some from the Leg 1 valve winding, and to a lesser extent from the Leg 3 line winding.

The strand bonding was best for CTC samples from the bottom of the coils and was worst for samples from the valve windings at the top.

The condition of the enamel on the strands was best for both windings at the bottom of Leg 1.

Some bundles of strands did not have a centre separator strip.

August 1998 Failure

Analysis of free and dissolved fault gases indicated conductor and cellulose overheating. Following the fault, 211 ppb of furfuraldehyde and <1 ppb of furfuryl alcohol were found in the oil whereas in 1996 only 30 ppb of furfuryl aldehyde had been detected.

At one location towards the bottom of the Leg 3 valve winding all discs were burnt open circuit through to the inter-winding cylinder. The strands in the outer disc of the valve winding adjacent to the bottom static ring were radically displaced over about 150° of the perimeter of the coil. The delta connected valve winding has a total of 31 strands. During salvage of the transformer the coils on the unfaulted legs were examined. On Leg 1 a total of 10 strands were found to be shorted, involving 6 strands in one bundle and 2 strands in each of two other bundles.

The paper wrap on the strand bundles was checked in manual tension. With the exception of the Leg 1 valve winding, paper samples from the bottom of the coils did not break in manual tension. In the case of paper samples from the top of the coils, those from the Leg 2 valve winding did not break in tension.

The strand bonding was worst for CTC samples from the Leg 1 valve winding at the bottom.

The condition of the enamel on the strands was best for both the Leg 1 and Leg 2 line windings at the bottom and worst for the Leg 1 valve winding at the bottom. The latter probably reflects the strand shorts.

Some bundles of strands did not have a centre separator strip.

Further information on the circumstances of the failures in 1994 and 1998 will be found in [1].

November 1999 Failure

In March 1999, an oil circulation pump failed resulting in ball bearings, part of the ball race and particles from the impeller and housing being pumped into the transformer. Within a few days of this event the transformer was taken out of service and was drained and cleaned. It was then refilled with oil, the pumps were operated and then it was drained and cleaned again. This process was repeated several times until evidence of metal particles had disappeared in accessible areas.

Following the in-service failure of the transformer in November 1999, analysis of the free and dissolved gases indicated arcing with evidence of burning of paper. Following the fault, 50 ppb of furfuraldehyde was found in the oil, while in May 1999 the level had been 18 ppb. Electrical tests

showed high exciting current on Leg 2 and the ratio for this leg indicated that there were shorted turns in the valve winding. Resistance measurements indicated that the Leg 2 valve winding was open circuited. Upon removal of the outer pressboard, shorted turns and open circuit strands could be seen at the top of the Leg 2 valve winding, as is shown in Figure 3.

The delta connected valve winding has a total of 31 strands. During salvage of the transformer, the coils on the unfaulted legs were examined. On Leg 1 of the valve winding, 7 of the strands were found to be shorted and a further 15 had reduced insulation resistance. On Leg 3, four strands were shorted and a further 7 strands had reduced insulation resistance.

In the case of the line winding, the strands could only be isolated at one end and measurement of the loop resistance of pairs of strands showed evidence of shorts involving about one third of the strands on Leg 1.



Fig. 3 November 1999 failure showing shorted turns and open strands involving Leg 2 of valve winding adjacent to top static ring

It was observed that the paper wrap on the CTC bundles was darker in colour for the valve winding compared to the line winding.

February 2000 Failure

Following the in-service failure, analysis of the free and dissolved gases indicated evidence of arcing and burning of paper. After the fault, 34 ppb of furfuraldehyde was found in the oil, while in September 1999 the level had been 32 ppb. Electrical tests showed high exciting current on Leg 2 and ratio measurements on this leg indicated shorted turns in the valve winding. Resistance measurements yielded higher values than normal for combinations involving Leg 2 of the ungrounded star connected valve winding.

The isolation and continuity of the strands on the unfaulted legs was not checked prior to the removal of the coils from the limbs of the core.

The star connected valve winding has two parallel bundles of CTC. The unique aspect of this failure is that the paper wrap on one bundle in the top disc was virtually incinerated on all three legs. An example is shown in Figure 4. In these locations



Fig. 4 February 2000 failure showing incinerated paper wrap on 1 of 2 CTC bundles of Leg 3 valve winding at top adjacent to static ring

the enamel on the strands had been destroyed. Figure 5 shows typical thermal damage to the enamel.

It was also observed in the case of Leg 2 that the bundles of CTC in the valve winding had been bent into somewhat of a clover leaf shape as is shown in Figure 6.



Fig. 5 February 2000 failure showing thermally degraded enamel on strands of Leg 2 valve winding at top of coil near static ring

Samples of CTC were recovered from the third disc from the top and from the third disc from the bottom of both valve and line windings. Sections were cut from the samples and positioned in a testing machine such that a radial force was applied at the mid point of the sample, tending to straighten the sample. The force required to deflect the CTC bundle 2.5 mm was measured. The valve winding CTC bundle measured 16 mm by 25 mm and the line winding CTC measured 14 mm by 29 mm. The measured values of force on the line winding CTC were normalized to those on the valve winding CTC using the relationship:

$$F_1/F_2 = (b_1 \times h_1^2 \times L_2)/(b_2 \times h_2^2 \times L_1)$$

where “b” is the width and “h” is the height of the CTC bundle and “L” is the distance between the support points near the ends of the sample.

Table II

Force to Radially Deflect CTC Bundle 2.5 mm Towards Core Feb 2000 Failure – Samples from 3rd Disc from Top or Bottom

Leg 1		Leg 2		Leg 3	
Sample	Newtons	Sample	Newtons	Sample	Newtons
Valve T	356	Line T	431	Valve T	623
Valve T	445	Line T	583	Valve T	632
Valve T	516	Line T	632	Line T	200
Valve T	645	Line T	841		
Valve T	676			Valve B	391
		Valve B	227	Valve B	525
Valve B	689	Valve B	249	Valve B	534
Valve B	806	Valve B	396	Valve B	569
Line B	454	Valve B	596	Valve B	574
Line B	903	Valve B	725	Line B	151
Line B	970	Valve B	827	Line B	600
		Line B	164		
		Line B	307		
		Line B	431		

Normalized force required to produce the same deflection in modern, oven cured CTC having a similar radius was 1270 N.

September 2000 Failure

Following the in-service failure, analysis of free and dissolved gases indicated conductor overheating with evidence of burning of paper. Following the fault, 65 ppb furfuraldehyde were found in the oil, while in June 1998 the level had been 19 ppb. Winding resistance measurements indicated that the valve winding was open circuited on Leg 1.

At the time of writing, this transformer has not yet been salvaged and thus analysis of the failure is incomplete.



Fig. 6 February 2000 failure showing distorted CTC bundles of valve winding at top of Leg 2

DISCUSSION OF FAILURES

It will be noted that two of the converter transformers failed 8 months and 11 years respectively after a pump failure that had introduced metallic particles into the transformer. However the similarity of all failures, including the four that were not preceded by a pump failure, suggests a different cause.

It can be observed that all six failures occurred at, or very close to a static ring. In this location there is some reduction in the cooling as a result of the insulation structure, and in addition, this location is exposed to stray flux as a result of the configuration of the tap leads, as well to stray flux inherently associated with the end of the coils.

Some of the unfaulted coils were found to have shorted strands and in these cases there was more evidence of thermal degradation. At what stage the strand shorts developed is unknown. It is known that the bond strength of the resin used

on modern CTC is substantially greater than that used 20 years ago.

In the case of the five more recent failures, the converter transformers had been equipped with continuous on-line monitoring of hydrogen-in-oil and in two cases multi-gas analyzers were installed as well. Although this type of monitoring equipment has proved very useful for transformers with core problems at high load [2], the continuous on-line gas-in-oil monitoring provided no warning of the impending failure of these five transformers.

Oil samples had been taken from these transformers on an annual basis for furan-in-oil measurements. While furan-in-oil had responded to an overheated, paper covered joint in one of these transformers in the past, and had also responded to overheating of a portion of a valve winding in a Bipole 1 single phase converter transformer, there was no significant furan production detected from any of these six Bipole 2 units based on annual samples.

ELECTRICAL ON-LINE DIAGNOSTICS

In an effort to improve our on-line monitoring, sensors have been installed at all bushing capacitance taps of the 16 converter transformers associated with Bipole 2 to facilitate periodic measurements of partial discharge activity. In addition, because 8 of these transformers have 230 kV bushings that are now 18 years old, and because the fault level on the 230 kV side of the converter transformers is high, continuous monitoring of these bushings using the sum-current (or Gamma) method has been implemented [3].

As was discussed in [1] we have also installed PD sensors on some of the Bipole 1 single phase converter transformers at the inverter. In addition, two generator step-up transformers have been equipped with both PD sensors and Gamma analyzers.

The PD sensors consist of ferrite core RF current transformers that are installed on the ground connection to the capacitance tap of the bushings as is shown in Figure 7. The partial discharge analyzer is based on two Yokogawa DL1540L oscilloscopes that can monitor 8 channels simultaneously. As is discussed in [4], the noise cancellation methods used by this analyzer include:

- Restrict bandwidth of measurement to 1 to 20 MHz.
- Reject specific phase ranges (e.g. thyristor pulses)
- Reject as noise, pulses exceeding predefined pulse width
- Reject pulses that correlate with known noise source
- Reject cross-coupled pulses based on magnitude

In the converter station environment we have found the use of pulse width to be a particularly useful means of rejecting noise.

Reference [1] discusses our experience with PD measured from one single phase converter transformer which tended to disappear after the transformer had been energized for a period of time. At the time of writing, sensors have been installed at the bushing capacitance taps of all Bipole 2 converter transformers within the past several months.

Recently, very high PD was measured from the capacitance tap of one 138 kV bushing of a 3-phase generator step-up transformer. The results of these measurements are shown in Figure 8.



Fig. 7 PD sensor at bushing capacitance tap

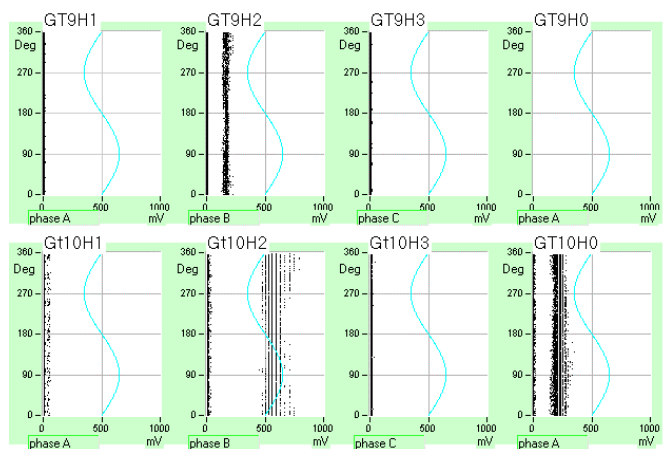


Fig. 8 On-line PD measurement from 138 kV bushings and neutral bushing of generator step-up transformers GT9 and GT10

It will be noted that a very high level of discharge activity was measured over the complete 360° of the 60 Hz voltage from the capacitance tap of the GT10 H2 bushing. Lesser activity was measured from the GT10 H0 (neutral) bushing which has

a RF CT attached to the ground connection. In addition, some response was also observed from the GT9 H2 bushing capacitance tap. These two transformers are connected in parallel by a short length of bus on the 138 kV side.

Upon investigation, it was found that the small capacitance tap bushing was loose on the 138 kV bushing of GT10 H2 and that there was evidence of oil leakage at this location. This 138 kV bushing has now been replaced. While the PD may have been as a result of a poor contact between the tap bushing and the condenser core, it is also possible that sufficient oil had been lost so as to expose the paper insulation of the bushing. A previous failure of a 138 kV bushing of a different type on one of the generator step-up transformers at the same station ultimately resulted in the failure of the transformer, a major oil spill and fire damage.

CONCLUSIONS

1. Six out of eight Bipole 2 Stage 1 converter transformers have failed for thermal reasons involving the CTC primarily in the valve winding. This may reflect restricted cooling, stray flux heating and/or the quality of the CTC.
2. Thermal deterioration of the insulation of paper wrapped bundles of resin bonded, enamel insulated CTC strands is not detected by continuous on-line gas-in-oil measurements.
3. Research on the detection of non-furan species typical of the thermal deterioration of the enamel coating of strands may be appropriate.
4. Electrical measurements of partial discharge activity are showing some promise for transformers as well as for the associated bushings.

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