Recent Transformer Failures within Eskom Transmission

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ABSTRACT
Typically transformers faults are clear-cut to diagnose. The use of protection trip information, DGA and electrical test generally provides an excellent indicator to pin point the fault. However, it must be noted that other transformer faults are far more complex to detect and require sound understanding of the transformer. In most of these causes there are only very small changes which are normally masked from the untrained eye. The paper describes cases that required basic and complex diagnoses to ascertain the root cause of the fault.

INTRODUCTION

In-service failure of the power transformers and shunt reactors is part of daily setbacks that transformer owners are facing, ESKOM is no exclusion. The life span of both transformers and reactors is in the range of few milliseconds to some years (40 years service life for a transmission transformer). After an in-service failure, it is important for a utility to investigate the failure so that the root cause of failure may be determined. Finding the root cause helps in deciding the future of the failed unit, and to timeously implement corrective actions on the other installed units of the same design/class.

Eskom Transmission has more than 550 power transformers in service with a power rating of 10MVA and above and representing an asset base of approximately 130,000MVA. There are about 90 shunt reactors representing an asset base of about 7500MVAr. The average age of these transformers and reactors is about 30 years and 25 years respectively, and these are beyond the midpoint of the transmission transformer expected life (40 years). It is important that all these failures i.e. whether aged units or brand new units are investigated so that root causes of failures can be determined. Root cause analysis enables Transmission to initiate modifications on units of the same class/make and to decide on the future of failed units.

DIGNOSTIC TECHNIQUES CURRENTLY EMPLOYED BY ESKOM

Diagnostic testing has become well entrenched within ESKOM Transmission. Oil analysis in the form of DGA has been performed for many decades at ESKOM. Electrical testing has also proven itself to be an effective and essentially tool in assessing the condition of the transformer it terms of its dielectric, thermal and mechanical properties. The combination of both these transformer diagnostic techniques has proven to be the most valuable way of diagnosing a transformer.

Electrical Test Types

The following electrical tests are used to determine the condition of the transformer:

Power Factor and Capacitance on windings and bushings: This test is used to assess the condition of the oil and cellulose in terms of moisture, ionization, carbonization, etc. The advantage of this method is that it identifies the winding (HV or LV) that has a possible problem.

10kV Ratio Test: This test is used to determine possible turn-to-turn or partial turn-to-turn failure.

10kV Excitation Current Test: This test is used to determine the condition of the core and tapchanger. It is performed on all tap positions.

Insulation Resistance Test: This test is used to determine the condition of the insulation under the influence of a DC voltage. Measurements are from windings to ground and core to ground.

DC Winding Resistance Test: This test is used to determine bad or loose connections on tap changers, bushings, broken strands, shorted turns and high resistance contacts in tap changers.

Impedance Measurements: This test measures the short circuit impedance on a transformer as a three phase equivalent. Measured values are compared to nameplate values to assess the mechanical condition of the transformer in terms of winding and core deformation.

Sweep Frequency Response Analysis (SFRA): This test passes a range of frequencies (between 10Hz to 2MHz) through the transformer and then calculates the transfer function. From these responses the mechanical condition can be assessed.

Chemical Test Types

Oil Quality Indicators: The oil quality indicators are moisture content, acidity, dielectric strength and interfacial tension.

Paper Condition Indicator: The concentrations of the paper degradation product 2-furfural (2FAL) provide an indication of the condition of the paper by converting to DP values.

Dissolved Gas Analysis (DGA): The DGA techniques (IEC, Roger's Ratios, CSUS) are used for assessing the condition of the transformer.

INFLUENCE OF TRANSFORMER DESIGN ON DIAGNOSTIC TEST

The use of the above diagnostic techniques can be misleading if the design of the transformer is not considered. The following are some typical design features that should be taken into account when conducting a diagnostic test program:

- The presence of an internally grounded electrostatic shield between the windings reduces the sensitivity of measurements of the dielectric characteristics of solid insulation.
- The presence of a waterproof dielectric (e.g. synthetic resin bonded paper (srbp) or cast resin cylinder) in the oil barrier space prevents the estimation of water content in pressboard barriers through measurement of dielectric characteristics.
- The presence of a dielectric material with inherent elevated dielectric losses in the winding support insulation (neutral coils) and tapping lead cleat bars masks the change in the condition of the main insulation.
- Internal connection of tertiary windings and neutral ends of star windings prevents the evaluation of the condition of inter-phase insulation and comparison between phases.
- The presence of resistors in the circuit of the core causes distortion of dielectric characteristics (increasing power factor/tan delta of LV-core; HV-core; and decreasing power factor/tan delta of HV-LV).
- The presence of poor insulation in the bushing tap insulation or internally grounding the last electrode (potential tap design) prevents evaluation of the oil condition and the core surface condition with the bushing through measurement of C2 dielectric characteristics.
- Grounding the magnetic core through direct contact, e.g. frames (core clamps) with the tank particularly and internal grounding the core generally, make difficult the identification and location of thermal faults caused by circulation currents.
- The presence of a capacitor or non-linear resistor installed on a regulating winding to control the distribution of surge voltages.
- The sensitivity of detection of hoop buckling by leakage reactance or capacitive measurements reduces with increasing voltage rating of the transformer (increasing inter-winding gap).

Controllability of design considerations needs to be addressed in specifications for new transformers and for modification of transformers during a life extension program. It should be remembered that there are other factors than design that impact on the effectiveness of diagnostic tests.

CASE EXAMPLE 1: SELECTOR FAULT

This transformer was manufactured in 2005 and operates at a voltage of 275/88/22 kV with a rating of 315 MVA. The transformer was removed from service as a result of the increasing trend in the methane and ethylene levels. Electrical tests were performed to establish the location and severity of the fault.

DGA Results

The DGA signature is given in Figure 1 below. The dominant hydrocarbon in the DGA signature is ethylene and methane in similar quantities. The relative levels of these gases indicate a localized thermal fault.

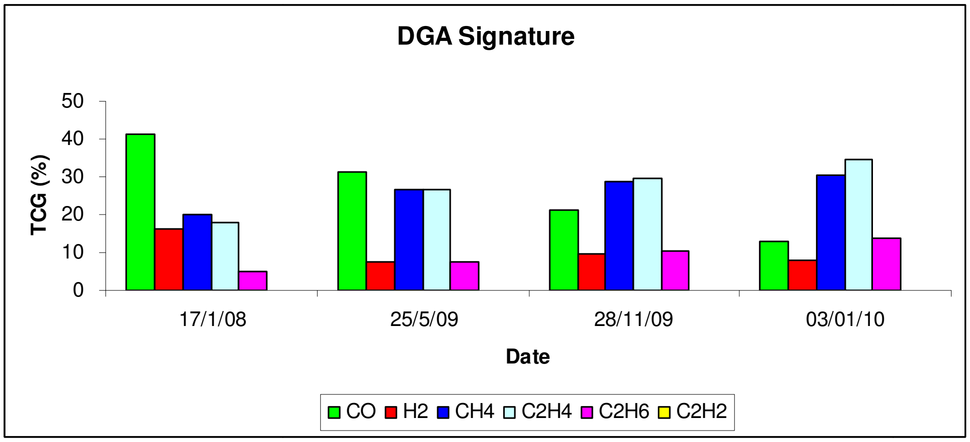

Figure1: DGA Signature for the Transformer

Power Factor

The winding power factor values are given below in Table 1. The power factor results revealed no indication of any insulation concerns.

Measured	Power Factor (%)	Capacitance (pF)
HV/MV winding to earth	0.23	8395.30
Between HV/MV and Tertiary winding	0.15	12039.3
Tertiary winding to earth	0.15	24280.0

Table 1: Winding Power Factor and Capacitance Test Results

Ratio Measurements

The ratio measurements are given in Figure 2 below. The ratio of the transformers was tested at 10kV. The ratio measurements revealed no significant concerns.

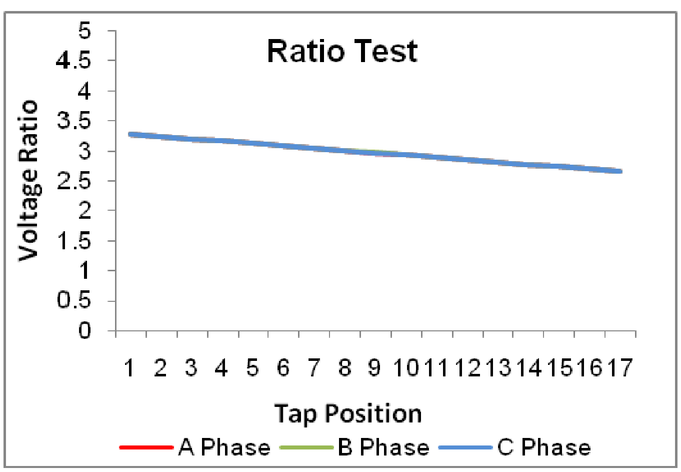

Figure2: Ratio Measurements

DC Winding Resistance

The DC winding resistance measurements are given in Figure 3 below. The measurements were performed at 15A.

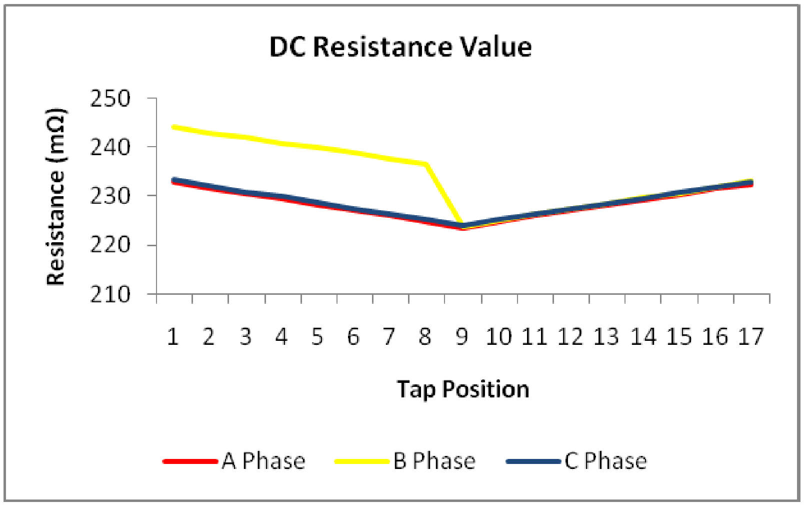

Figure 3: DC winding resistance values

The DC winding resistance test results compare very well between the A and B phase. However, it must be noted that there is an increase in the resistance on the B Phase from tap 1 to 8 when compared to the other two phases, possible the effect of the change over switch within the selector. The MV and tertiary resistance were within acceptable limits.

Impedance

The measured impedance is give below in Table 2, 3 and4.

HV to MV: Three Phase Equivalent Tests

Tap	Nameplate Impedance (%)	Measured Impedance (%)	Change in Impedance (%)
1	13	13.106	0.796
5	13.1	13.169	0.515
17	14.1	13.965	0.966

Table 2: HV to MV: Three Phase Equivalent Test Results

HV to Tertiary: Three Phase Equivalent Tests

Tap	Nameplate Impedance (%)	Measured Impedance (%)	Change in Impedance (%)
1	43.6	43.732	0.289
5	42.7	42.805	0.232
17	40.2	40.443	0.594

Table 3: HV to Tertiary: Three Phase Equivalent Test Results

MV to Tertiary: Three Phase Equivalent Tests

Tap	Nameplate Impedance (%)	Measured Impedance (%)	Change in Impedance (%)
5	27.9	27.777	0.473

Table 4: MV to Tertiary: Three Phase Equivalent Test Results

All impedance measurements are within acceptable limits.

Insulation Resistance

The values measured for Core-Earth was 1.97GΩ indicates that the core is clear.

Sweep Frequency Response Analysis (SFRA)

All open and short circuit measurements were performed on the transformer. The only indication of a fault was on the short circuit measurement of the HV winding. This is given below.

Figure 4: HV Winding to Neutral Short Circuit Response

The short circuit test revealed no difference in the resistance and impedance between the HV winding. The comparison between the phases finds that the responses demonstrate a characteristic pattern and has good correspondence across the entire frequency range. These responses indicate no winding deformation.
There is a clear variance from about 750 kHz to 1 MHz. These variances may allude to the deformation of tapchanger and main winding leads.

Internal Inspection

Based on the DGA and electrical tests it was concluded that the fault was restricted to the tapchanger selector. An internal inspection then followed clearly identified the problem on the tapchanger selector.

Figure 5: Overheating on the Selector Contact 11.

CASE EXAMPLE 2: SHORTED TURNS

This transformer was manufactured in 1967 and operates at a voltage of 400/275/22 kV with a rating of 400MVA. This transformer tripped out of service in January 2010, 3 seconds after a pole mounted transformer supplied from its tertiary terminals had tripped on phase-to-phase-earth fault. An oil sample was taken and electrical tests performed to assess the extent of the damage.

DGA Result

The DGA signature is indicative of a normal operating transformer up to 06/04/2009. However, the DGA signature on the 20/10/2009 shows a significant increase in hydrogen levels. The DGA signature with this unusually high levels of hydrogen are attributed to a partial discharge type of fault, although low level thermal faults also sometimes have this signature. The DGA signature on the 01/20/2010 shows significant levels of hydrogen, acetylene, and methane. This DGA signature is indicative of dielectric fault.

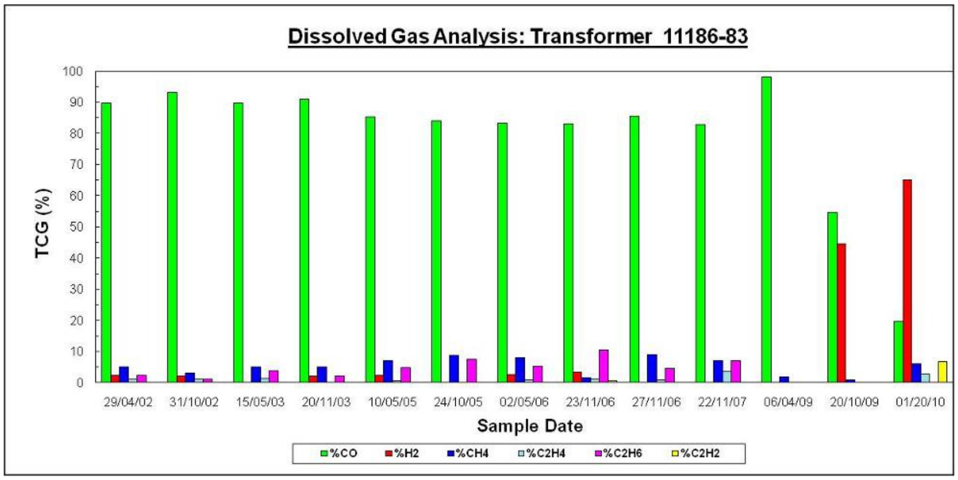

Figure 6: DGA Signature for the Transformer

Power Factor

The winding power factor values are given below in Table 5. The winding insulation results for the Tertiary winding to earth show significant concerns of the insulation system (oil and cellulose).

Measured	Power Factor (%)	Capacitance (pF)
HV/MV winding to earth	0.40	8 494.50
Between HV/MV and Tertiary winding	0.19	7 919.20
Tertiary winding to earth	0.67	16 537.50

Table 5: Winding Power Factor and Capacitance Test Results

Ratio Measurements

The ratio measurements are given in Figure 2 below. The ratio of the transformers was tested at 10kV. The inability to make a measurement on the A Phase is a clear indication of a winding fault possibly a shorted turn on the Red phase.

Tap	A Phase	B Phase	C Phase
1	Unable to measure	1.2716	1.2726
2		1.2757	1.2766
3		1.2799	1.2806
4		1.2841	1.2848
5		1.2884	1.2891

Table 6: Ratio Measurements

Exciting Current
The exciting current measurements are given below in Table 7. The exciting currents were performed at 10kV.
The inability to make a measurement on the A Phase limb is a clear indication of an imbalance in the magnetic circuit the effect of a shorted turn.

Tap	A Phase	B Phase	C Phase
	Current (mA)	Current (mA)	Current (mA)
1	Unable to measure	79.899	79.858
2		77.094	77.236
3		74.408	74.764
4		71.892	72.625
5		69.487	70.635

Table 7: Exciting Current Measurements

DC Winding Resistance
The DC winding resistance measurements for the Tertiary windings are given in Table 8 below. The measurements were performed at 15A. The Tertiary DC winding resistance shows resistance increase in the A phase only.

Tap	A Phase	B Phase	C Phase
	Resistance (mΩ)	Resistance (mΩ)	Resistance (mΩ)
1	277.45	251.30	250.28

Table 8: Tertiary DC Winding Resistance Test Results

Sweep Frequency Response Analysis (SFRA)
All open and short circuit measurements were performed on the transformer.
Tertiary Winding Open Circuit Open Circuit
There is a clearly a variance on the Red Phase (A Phase) of the winding. This variance is attributed to an imbalance in the reluctance on one of the core limb (A limb). This is indicative of a shorted turn fault that has this effect, which produces this characteristic change in the low frequency response.

Figure 7: Tertiary Windings Open Circuit Response

Internal Inspection
The test results clearly identified a problem with the A Phase Tertiary winding and hence an internally inspection for the transformer is required to assess the damage to the tertiary windings. The transformer was eventually scrapped and during the dismantling, an interturn fault was found on the tertiary winding of the A phase.

CASE EXAMPLE 3: FLOATING POTENTIAL

This shunt reactor was manufactured in 1977 and operates at a voltage of 400kV (22kV aux) with a rating of 100 MVA. This transformer tripped out of service on 2 February 2010 at 04:12. The Main1 & 2 Bucholtz Relays operated which operated the Master trip relays. The inspections were carried out in the yard but nothing could be found to relate to the trip. The DGA samples taken after the incident indicated elevated gasses, confirming the fault.

DGA Result
The DGA signature clearly shows a high level of acetylene for a long period of this Reactor's life. The DGA signature is possibly the result of sparking or arcing between bad connections of different or floating potential eg, winding clamping bolt sparking

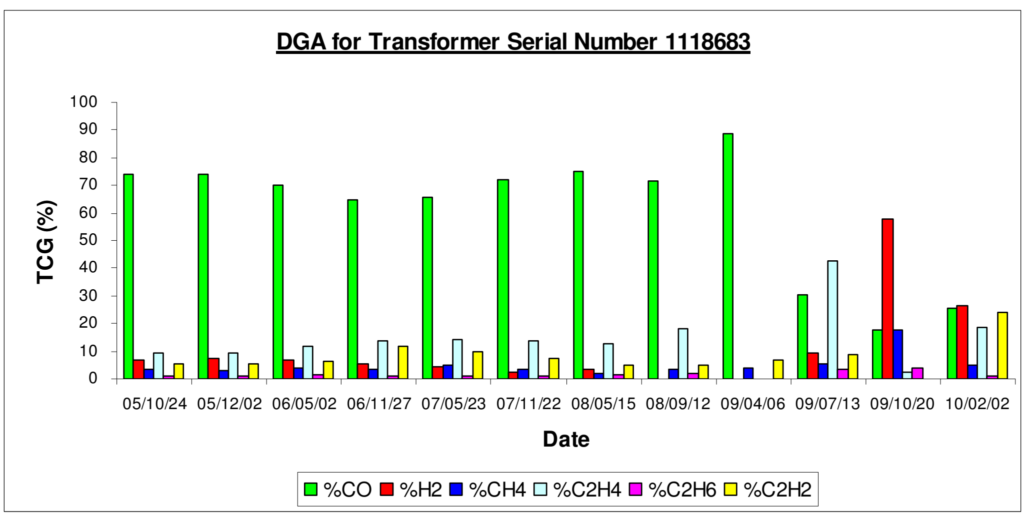

Figure 8: DGA Signature

Power Factor

The winding power factor values are given below in Table 9. The power factor measurements are higher than what would be expected for this reactor. This could be the result of the fault suffered by the reactor, which is evident by the DGA.

Measurement	Pf (%)	Capacitance (pF)
A phase to Earth	0.54	2850.40
A phase to B phase	0.55	182.92
B Phase to Earth	0.53	2742.80
B Phase to C Phase	0.56	207.16
C phase to Earth	0.53	2903.30
C phase to A phase	0.74	12.139

Table 9: Winding Power Factor and Capacitance Test Results

DC Winding Resistance

The DC winding resistance measurements for the windings are given in Table 10 below. The DC winding resistance test results are within acceptable limits.

A Phase Resistance (Ω)	B Phase Resistance (Ω)	C Phase Resistance (Ω)
2.3645	2.3588	2.3335

Table 10: DC Winding Resistance Test Results

Sweep Frequency Response Analysis (SFRA)

All open and short circuit measurements were performed on the transformer. The comparison between the phases finds that the responses demonstrate a characteristic pattern and has good correspondence across the most of the frequency range. These responses indicate no winding deformation.

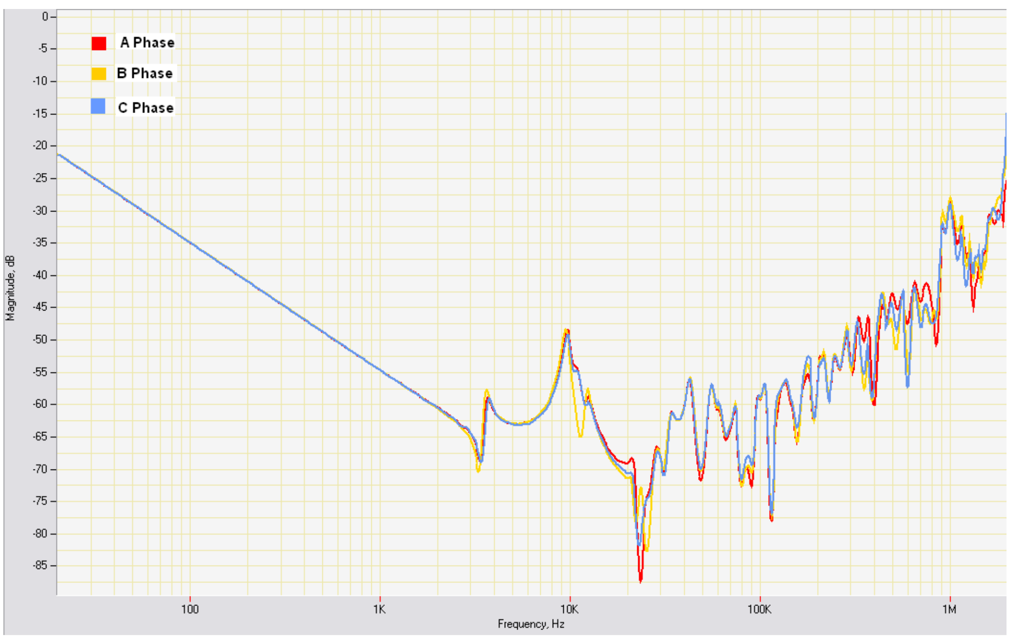

Figure 9: HV Winding to MV Windings Open Circuit Response

Internal Inspection
It was found that one of the brackets that support the tap changer diverter switch barrel had fallen off and damaged one of the selector switch leads (lead number 10). As a result a floating potential was caused by the bracket chopping off the lead.

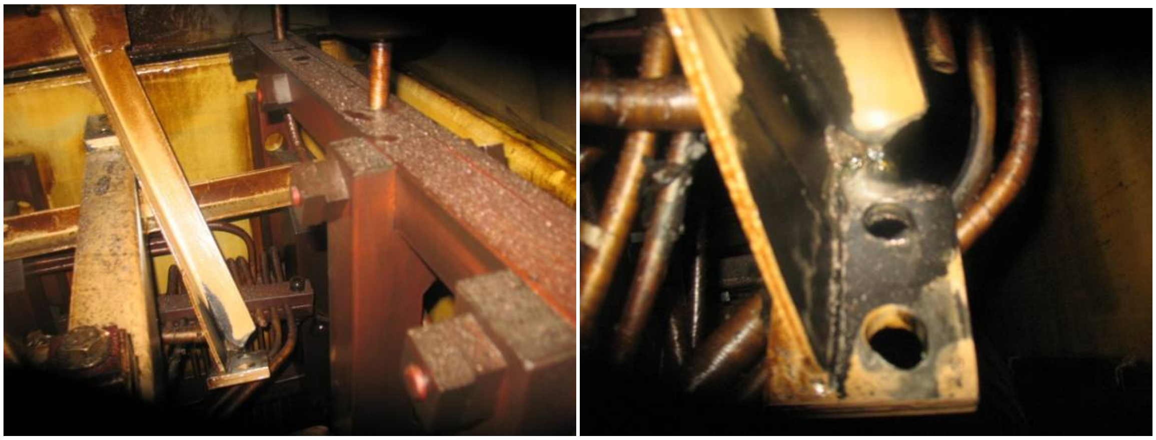

Figure 10: Floating Potential Fault

CONCLUSIONS

These case examples have provided a salutary warning/reminder that transformers which are operating apparently normally on the system can in fact be seriously damage, even though this may not be obvious from routine condition monitoring. Clearly such transformers would be much more likely to suffer an ‘unexpected’ failure and cause a forced outage, particularly if they experience unusual system or environmental events such as through faults, lightning strikes or switching transients.
In view of the seriousness of transformer failures it is important that all routine condition monitoring information (usually only DGA results) are scrutinized with the utmost care for any subtle indications of developing problems.
Since opportunities for off-line diagnostic tests are rare it is essential that the most is made of these opportunities. It is notoriously difficult to detect problems inside transformers, so diagnostic techniques should be as sensitive and discriminating as possible and implemented under conditions which ideally allow an evaluation to be made on the basis of the results of only one test, without relying on trend analysis. In our experience the effectiveness of capacitance and power factor measurements is greatly enhanced when separate measurements can be made on the three phases, so that this should be attempted whenever possible, even if it requires temporary disconnections inside the transformer.
If effective diagnostic techniques can be combined with a comprehensive database which allows comparison with reference results for transformers of the same design then it is possible to build up a capability to detect damage inside transformers before failure. This in turn allows pro-active asset management decisions to be made which can avoid unplanned outages and provide a sound basis for a targeted and justified asset replacement program – but this does require a commitment to a program of condition assessment testing.

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