ANALYSIS OF TRANSFORMER FAILURES AT ETHEKWINI ELECTRICTY

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ABSTRACT
This paper presents the use of electrical and chemical testing techniques as a diagnostic tool to identify and assess defects and/or failure conditions on power transformers. Four practical case studies are discussed that demonstrate the effectiveness of these techniques. These techniques have been successfully applied within eThekwini Electricity (TE) for the detection of possible faults and/or problems within a transformer.

INTRODUCTION
Today, utilities and other electrical power equipment operators are under pressure to provide a high level of energy supply quality with respect to availability and quality of voltage. The unexpected failure of a power transformer can result in a very large forced outage cost, exceeding the capital cost of the transformer. There is therefore a need to detect and locate suspect units rather than wait for imminent failure. Furthermore, when faults do occur, there is a need to identify the type and location of the fault quickly enough to aid with the execution of the appropriate maintenance thus reducing downtime. This puts great importance on diagnostic testing and interpretation thereof. There is therefore a need for appropriate (i.e. efficient yet cost effective) non-invasive condition monitoring tools and techniques to allow for early detection of defects and also for the analysis of faults. TE performs electrical and chemical tests to obtain a good perspective of the condition of their power transformers, thereby reducing and in some instances preventing massive damages and costs. A number of cases are presented in the paper which shows how the diagnostic tools have aided in decisions making.

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

ETHEKWINI ELECTRICITY'S EXPERIENCE

TE's HV Substation Division is responsible for the maintenance of over 250 transformers operating at primary voltages between 275, 132 and 33 kV with ratings from 315 to 15 MVA. The average age of these transformers are 25 years. Notwithstanding their age, these transformers have proven to be very reliable. The experience thus far has shown that the failure rates are less than 0.1%. Condition assessment of these transformers takes into account the chemical, electrical and mechanical conditions of the transformer. The availability of these test results allows Asset Managers to make informed decisions on the following possible actions:

i. Replacement of the transformer before end of life;
ii. Refurbishment of the transformer;
iii. Carry out corrective maintenance;
iv. Postponement of maintenance; and
v. Adjustments in loading of the transformer.

TE has placed great emphasis on obtaining and understanding the condition of all the transformers in their network, through the introduction of advanced diagnostic tools. TE's approach to condition assessment on transformers began in 2000 and to date 80% of the transformers have been fingerprinted.

As a standard practice TE performs tests under the following conditions:

i. On all new transformers for fingerprinting purposes;
ii. As part of routine electrical tests;
iii. After relocation;
iv. After repairs to tapchangers;
v. After any vacuum treatment, purification and regeneration;
vi. After a fault; and
vii. After any form of intrusive maintenance.

The following case studies illustrate how effective and efficient these tests and interpretation techniques proved to be, especially for some tricky asset (maintenance) management decisions.

CASE STUDY 1: 315 MVA AUTOTRANSFORMER FAILURE

Background

On 19 February 2007, a 275/132 kV, 315 MVA 3 phase auto transformer, manufactured in 1982, tripped on differential protection (red and blue phases), main tank and tap change pressure. The tap changer selector and diverter are made of 3 separate units and suspended from the main lid. The selectors reside in the main tank, whilst the diverters are housed in sealed cylinders. The main tank and diverter oils are separated from each other to prevent contamination.

At the initial site inspection, the blue phase pressure relief plate was found to have been blown out from the diverter head cover (see **Figure 1)** and landed on the ground, about 5 metres away. The main tank pressure relief valve had operated (see **Figure 2).** No other external damage was visible.

Figure 1: Pressure relief plate blown out from B phase diverter head cover

Figure 2: Main tank pressure relief valve operated (yellow pin sticking out)

Diagnostic tests and internal inspections were subsequently performed on this transmission transformer.

Diagnostic Test Results

a) Power Factor and Capacitance Test
The power factor and capacitance test results is given in **Table 1**.

Table 1: Power Factor and Capacitance Results

Date	Power Factor (%)			Capacitance (pF)		
	C_H	C_{HT}	C_T	C_H	C_{HT}	C_T
10/08/2006	0,49	0,57	0,51	8027,10	7511,5	19348
20/02/2007	0,71	0,74	0,73	7909,10	7675,5	20122

Note: C_H = HV (including MV windings) and tank
C_{HT} = HV/MV windings and Tertiary windings
C_T = Tertiary windings and tank

The winding capacitance compare well with previous historical results and are not indicative of a problem with this transformer. The winding power factor test showed a significant increase from the historical results. This is expected as the result of the main tank pressure relief operation.

b) Exciting Current Test
The tests performed on 20 February 2007 after the transformer had tripped indicated problems on the white and blue phase. When compared to historical test results, the white phase exciting currents had increased by an average of 47%. This significant increase is indicative of a tapchanger or short circuit problem. The blue phase exciting currents indicated a high resistance fault in the tapchanger.

c) Ratio Test
From the ratios measured on 20 February 2007, the red and blue phases had a number of taps not within acceptable limits. Ratio measurements were not within acceptable limits on the blue phase.

d) SFRA Tests

The SFRA results are given in **Figure 3**.

i) HV to MV winding open circuit

There is clearly a significant difference in the Blue phase when compared to the other two phases. This is a result of a shorted turn failure. A shorted turn has the effect of creating an imbalance in the reluctance on one of the core limbs (in this case the blue trace), which produces this characteristic change in the low frequency response. Excitation current and ratio test supported this diagnosis.

However, there is also a variance on the Blue phase when compared to the other phases in the mid to high frequency range. This variance is indicative of winding deformation. This variance warranted an internal inspection.

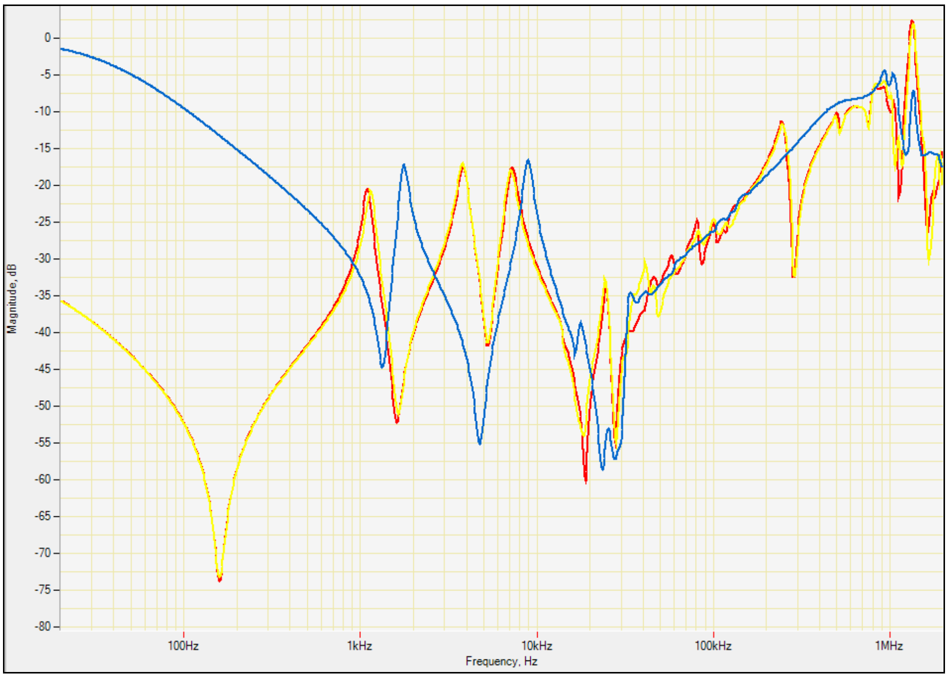

Figure 3: HV to MV winding response

e) Oil Condition Assessment

i) Oil and Paper Quality

The oil quality indicators, that of moisture content, acidity and dielectric strength, all indicated normal aging. The concentration of the paper degradation product 2- furfural (2FAL) was not measured in oil and therefore an analysis of the paper could not be performed for this transformer.

ii) DGA Analysis: The DGA signature is given in **Figure 4**.

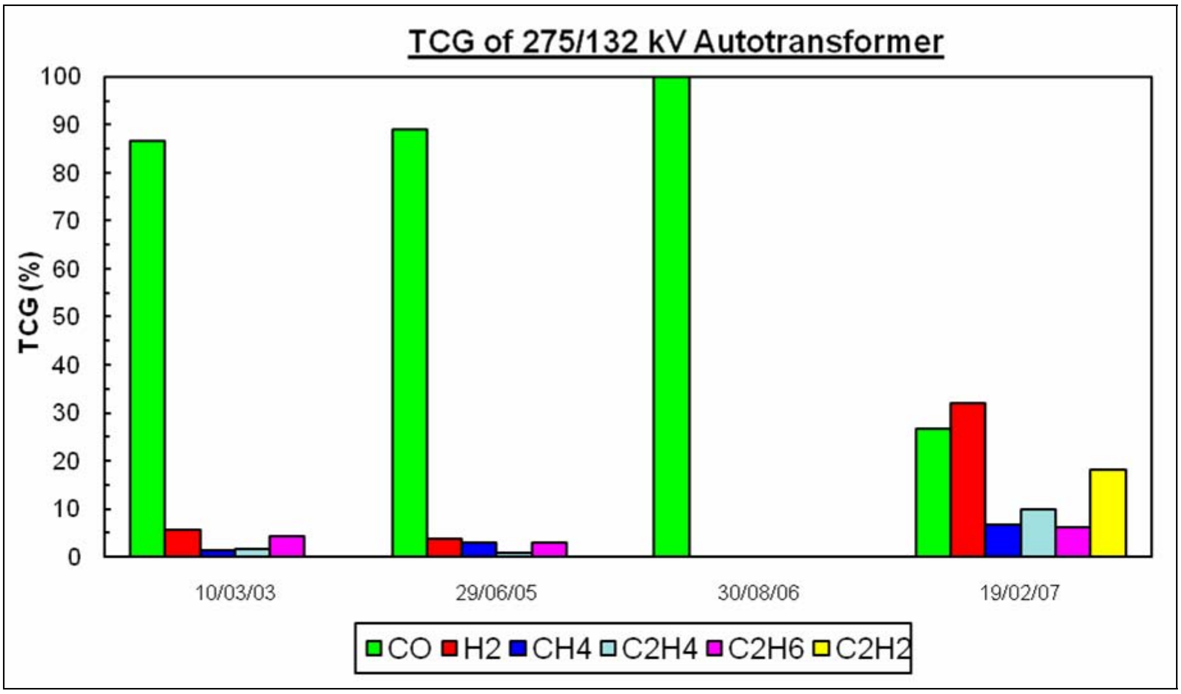

Figure 4: DGA Signature

The DGA signature for this transformer indicated normal operation. Oil purification was performed on the 30/08/2006. The oil purification was performed after diverter maintenance and modification. In hind sight at least one more oil sample should have been performed at the diverter maintenance. The DGA signature of the failure is typical of a dielectric fault.

Conclusions from test results

From the results the following was concluded:

i. Contamination of the insulation system of the transformer;
ii. Abnormalities/damage to the tapchanger; and
iii. Possible deformation of the Blue phase main and tap windings.

Internal Inspection Conducted

After the analysis of the diagnostics test results, an internal inspection was performed on the diverter, selector and main tank.

a) Diverter

The following damage was found on the blue phase diverter, which is shown in Figure 5 when removed from the transformer:

i. Blown out pressure relief plate incorporated in the head cover casting.
ii. Burnt flexible lead which connects metal parts to the common contacts which connect to the take-off terminal. See Figure 6.

Figure 5: Blue phase diverter

Figure 6: Blue phase diverter- Flexible lead burnt

b) Internal Inspection of Selector

The blue-phase selector revealed the following:

i. Moving contacts connected to terminals 5 and 6 on blue phase, (tap positions 3 and 4 respectively, whereas these are on terminals 6 and 7 on red and white phases, (taps 5 and 6). See Figures 7 and 8.

ii. Severe burns due to flashover and arcing of fixed contacts and collector rings. See Figure 9.

iii. Broken insulating supports. See Figure 10.

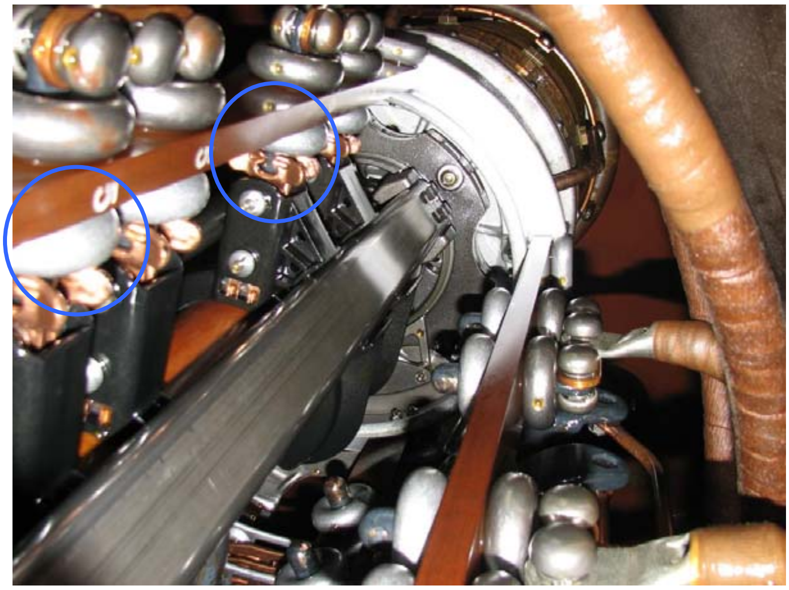

Figure 7: Blue phase selector- terminals 5 and 6 connected

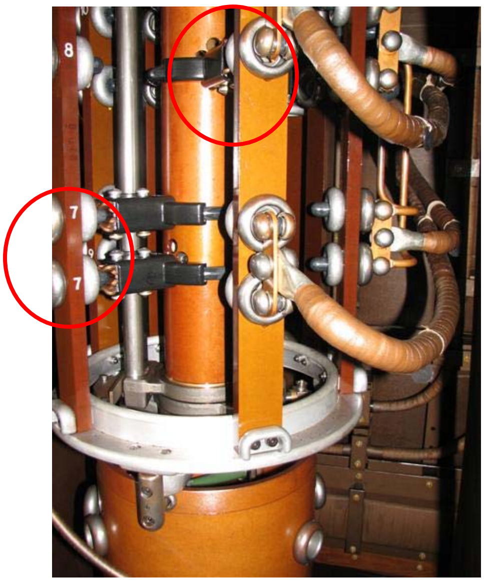

Figure 8: Red phase selector- terminals 6 and 7 connected

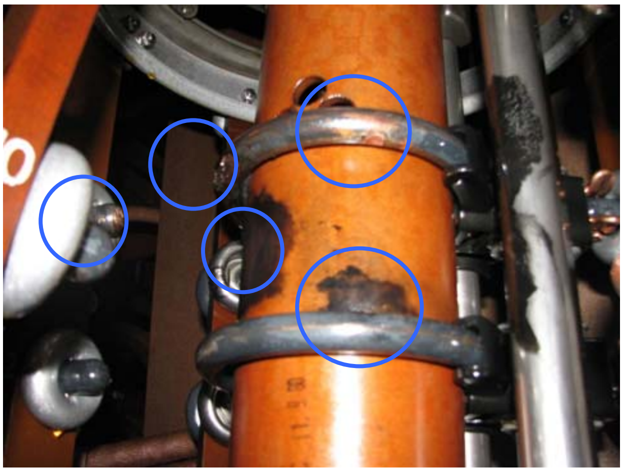
Figure 9: Flash marks on fixed contacts and collector rings

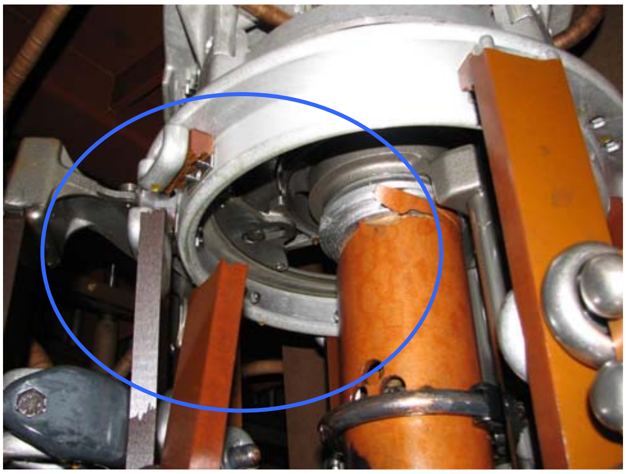
Figure 10: Broken insulator supports

c) Windings in Main tank

The main tank revealed the following:

i. Blue phase tapping leads and cleats: Severe distortion of the tapping leads external to the windings due to fault current forces, and paper insulation damage. See Figure 11.
ii. Numerous cleats and bolts were dislodged and broken and fell to the bottom of the transformer.


Figure 11: Blue phase tapping leads and broken cleats

Analysis of visual inspections

It is clear that there was a flashover at the Blue phase selector, which partially burnt: (1) a shield cap for a nut at the changer over switch, (2) a fixed contact, and (3) a collector ring. Since the oil appeared clean, the flashover would have been caused by an over-voltage, and this would have originated from either: (1) an external source, or (2) a problem in the Blue phase winding. The operating and support metal parts in the selector and diverter are linked via the metal operating shaft. Hence the fault current in these items in the selector flowed to the diverter and then to the common terminal which caused the flexible lead to burn off (see figure 6). This is further supported by the fact that a potential strap in the diverter chamber was also burnt off. These resulted in the overpressure in the diverter.

CASE STUDY 2: 60 MVA AUTOTRANSFROMER FAILURE

Background

A 132/88/6.6 kV autotransformer, manufactured in 1982, and rated at 60 MVA underwent its routine maintenance tests.

Diagnostic Tests Performed

a) Power Factor and Capacitance Test
The power factor and capacitance test results were within acceptable limits.

b) Ratio Test
The ratio test results were within acceptable limits.

c) Excitation Current Test
The excitation currents were within acceptable tests.

d) SFRA Test
The results are given in **Figures 12, 13, 14 and 15**.

i) HV to MV winding open circuit response
There are clear variances on the middle phase at frequencies between 20 kHz and 400 kHz when compared to the other two phases. There is a clear frequency shift in the middle phase. These frequency shifts are indicative of hoop buckling.

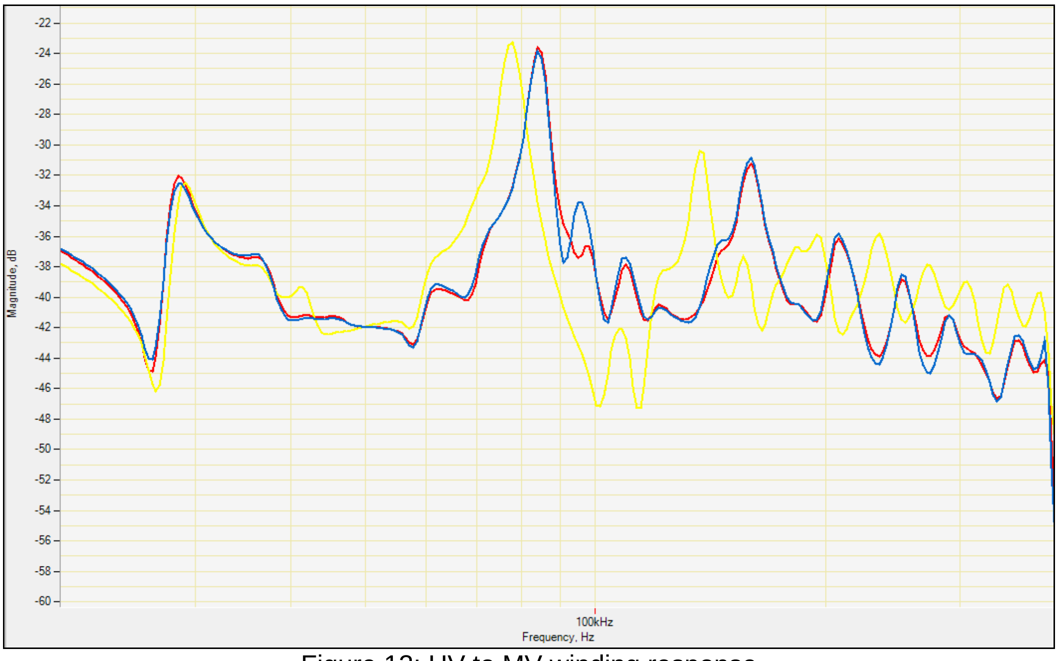

Figure 12: HV to MV winding response

ii) MV winding to neutral open circuit response
Very similar frequency shifts are evident on the white phase at frequencies between 20 kHz and 400 kHz when compared to that identified on the HV winding. These frequency shifts are indicative of deformation in the MV windings.

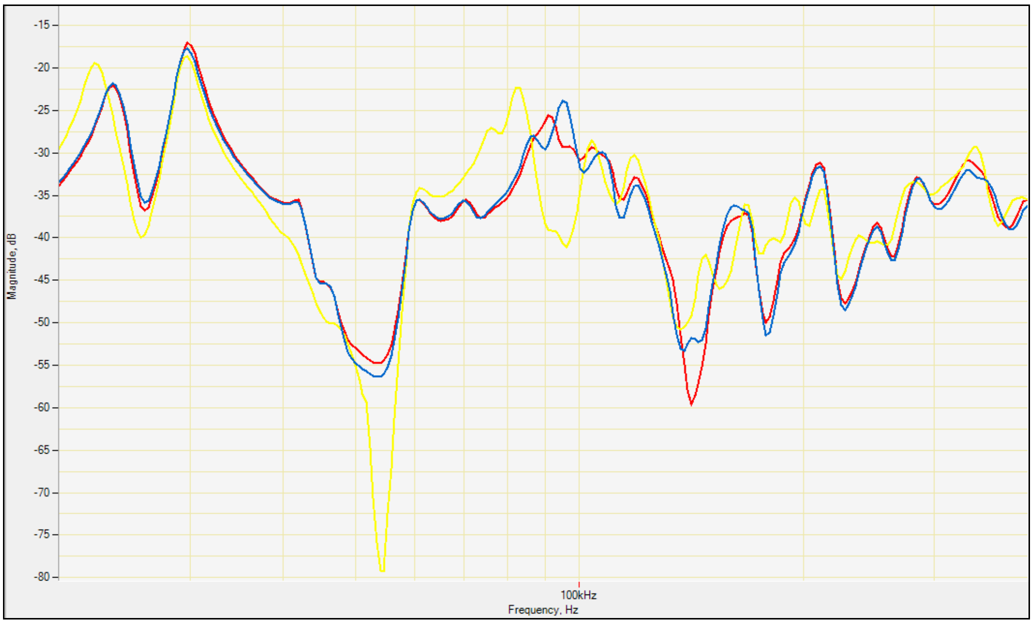

Figure 13: MV winding to neutral response

iii) HV Short Circuit response

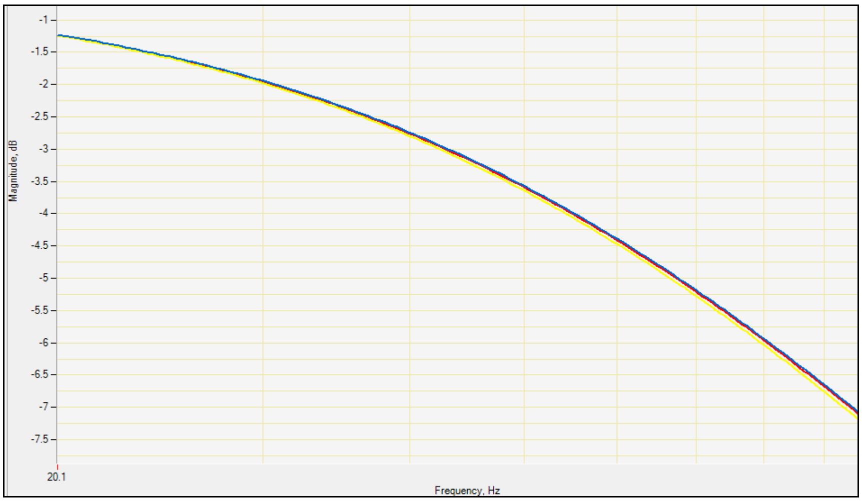

Figure 14: HV Short circuit response

The HV Short circuit test revealed no resistance or impedance change between the phases.

iv) MV Short Circuit response

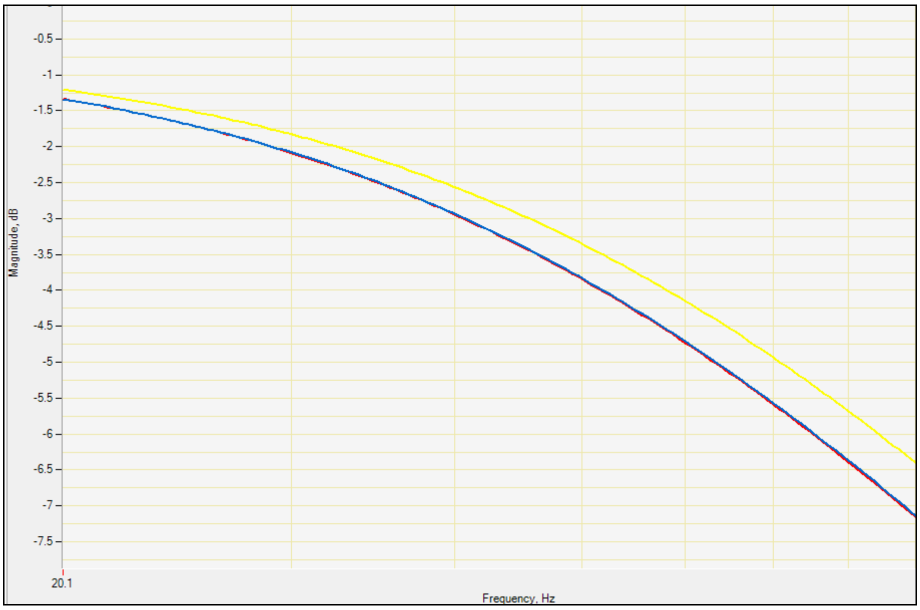

Figure 15: MV Short circuit response

The MV Short circuit test revealed a resistance and impedance change when compare to the other phases. This is a clear indication that the deformation is restricted to the MV winding.

e) Oil Condition Assessment
   i) Oil and Paper Quality
      The oil quality indicators that of moisture content, acidity and dielectric strength, all indicate normal aging. The concentration of the paper degradation product 2- furfural (2FAL) was not measured in oil and therefore an analysis of the paper could not be performed for this transformer.

Conclusion
The SFRA revealed MV winding deformation possible a hoop buckling condition. Upon inspection the following was noted as shown in **Figure 16**.

Figure 16: MV White Phase

CASE STUDY 3: 25 MVA TRANSFORMER FAULT

Background
A 33/11 kV 25 MVA Dy11 transformer, manufactured in 1981 tripped on transformer differential protection. Diagnostic tests were performed on this transformer.

Diagnostic Tests

a) Exciting Current Test
The exciting current revealed problems on Taps 9 and 10 for the red and white phases. This indicated of possible shorted turns or tapchanger problems.

b) Ratio Test
The ratio test also revealed problems on Taps 9 and 10 for the red and white phase.

c) SFRA Test: The SFRA test result in given in **Figure 17**.
i. HV Winding Open Circuit
The responses clearly indicate a problem on the White phase.

Figure 17: HV to MV winding response

e) Oil condition Assessment
i) Oil and paper Quality
The oil quality indicators that of moisture content, acidity and dielectric strength, all indicate normal aging. The concentration of the paper degradation product 2- furfural (2FAL) was not measured in oil and therefore an analysis of the paper could not be performed for this transformer.

Visual Inspection
The inspection results are given in Figures 18, 19 and 20. There was a clear indication of a flashover between the red phase and ground. This flashover caused damage to the spur gears, as shown in Figures 20 and 21. There was excessive carbonization of the oil and significant sludge buildup.

Figure 18: View of the Ferranti DS2 tap changer with cover removed

Figure 19: Flashover from Red phase current collector to ground via “insulating” gears.

Figure 20: Damaged main gear

<u>SFRA After Repairs</u>

The repairs involved replacement of the fixed and moving contacts, and the damaged gears. On-site oil purification was also performed. The SFRA result after repairs is shown in **Figure 21**. The results showed that the problem was remedied. The transformer was subsequently switched on.

<u>Figure 21: SFRA after repairs to tap changer</u>

CASE STUDY 4: 15 MVA TRANSFORMER FAILURE

Background

A 33/6.6 kV 15 MVA Dy11 transformer, manufactured in 1963, tripped on earth fault in December 2004. The fault was traced to a flashover in the diverter. The extent of the fault is shown in F**igure 22**, and repaired as shown in **Figure 23**. Diagnostic tests were performed on 12 January 2005. The test results were found to be acceptable and the transformer was subsequently put back into service. The transformer tripped in March 2005. Various diagnostic tests were performed just after the fault, in particular the exciting current test. The results are given below.

Figure 22: Flashover in diverter- phase to earth fault

Figure 23: Barrier board and insulator after repairs

Diagnostic Tests

a) Exciting Current Test
The exciting current test was done for all 15 tap positions. This test, performed on 5 March 2005, gave much higher exciting current values when compared to a previous test result. Some of the results are given in **Table 2**. At first, it was thought that the core was magnetised. However, after demagnetising the core, the exciting current values were still relatively high. The huge increase in all phases was then attributed to a tapchanger related problem.

Table 2: Exciting Current Test Results

Tap	**Red Phase**		**White Phase**		**Blue Phase**	
	12/01/2005	**05/03/2005**	**12/01/2005**	**05/03/2005**	**12/01/2005**	**05/03/2005**
	Current (mA)		**Current (mA)**		**Current (mA)**	
1	65.145	100.22	44.880	80.202	67.227	101.00
7	74.221	113.66	42.577	91.109	76.171	114.04
15	90.811	137.12	52.398	110.65	91.944	137.30

Initial Visual Inspection

The selector and diverter are housed in separate compartments, see **Figure 24**. Visual inspections of these items were performed. The tap changer was operated throughout the tapping range to check for mechanical problems. No defects were noted apart from burns on the arcing contacts in the diverter, and since these contacts were made of only copper and not copper-tungsten tipped as would be the case for arcing contacts, it was initially thought that the burn marks were normal wear and tear, see **Figure 25**. There were no other visible signs to indicate a fault in the tap changer. The contacts were lightly dressed, diverter filled with oil, and made ready for testing.

Figure 24: Diverter shown opened below and

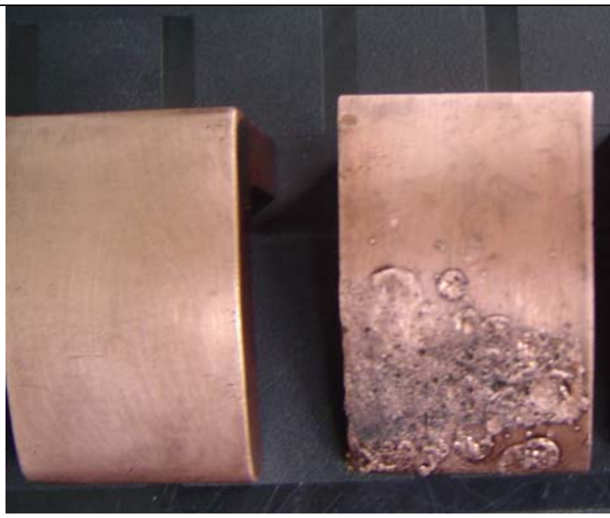

Figure 25: Diverter contacts

selector above	

b) Exciting current test after repairs
When the test was performed, the exciting current was relatively high as per the previous tests. At some tapping points the current rose beyond the instrument limit and no reading were obtained. The diverter compartment was then opened and the tests repeated. Significant arcing was observed during the transition period, as shown in **Figure 26**. It was then suspected that there was a break-before-make condition. This was, however, not visible due to the high speed operation. To confirm this, the operating rod was disconnected from the mechanism box and a slow close performed. The suspicion was confirmed- it was found that there was indeed a break-before-make condition. There were various possible reasons why this happened. A sister transformer was then inspected to ascertain the required operating process, and this transformer contacts were adjusted accordingly. The exciting current tests were performed once more, and the test was successful. The transformer was subsequently commissioned.

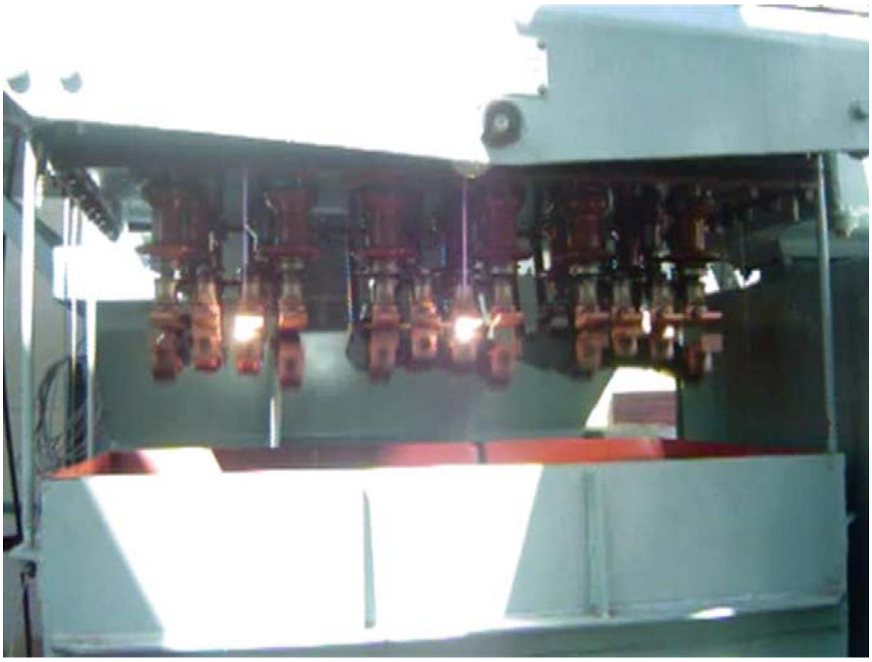

Figure 26: Arcing in diverter during exciting current test

CONCLUSIONS

(1) The numerous diagnostic tools available to Maintenance Managers can be effectively used to monitor transformer condition, fingerprint healthy transformers and aid in effective analysis and identification of failures and the failure mechanisms, thereby aiding in the implementation of appropriate maintenance interventions.

(2) DGA interpretation in particular aids by differentiating between dielectric and thermal faults. The value of power factor, ratio tests, and excitation currents is once again verified and implemented to detect the cause and location of a fault. SFRA measurements have proved to be a reliable means of detecting winding movement damage, even if reference results are not available.

(3) Signatures prior to faults are useful for comparisons with tests results after faults. Since opportunities for off-line diagnostic tests are rare and limited, it is essential that most is made of any outage window of opportunity by performing the relevant tests.

(4) The four cases of transformer failures have shown that the ability of the diagnostic tool to aid in failure analysis depends on the nature of the fault; hence not all of them will point to the fault. This highlights the need to apply as many of the tools as possible, and apply such in a complimentary manner.

(5) In view of the increasing costs of transformer forced outages and unexpected failures it can be seen that eThekwini Electricity's progressive practice in terms of transformer maintenance, and use of the appropriate diagnostic test techniques for fault analysis, has thus far proved to be reliable and cost effective to the company.

(6) In general, the use of diagnostic test tools and techniques enhances the condition monitoring and assessment process for transformer, both when in service and when faulted, thus allowing for informed decisions making by asset managers.

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