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CONDITION-BASED ASSESSMENT OF ON-LOAD TAP CHANGERS

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INTRODUCTION

On-load tap changers (OLTCs) are a crucial element of utility networks, as they must operate in a precise fashion in order to maintain a constant voltage output. This must be achieved regardless of variation on input or load. OLTCs have been a weak link in many networks, as they deteriorate over time due to mechanical problems or contact wear from repeated operation. Erosion of the contacts over time is expected due to the nature of their function. Coking of the contacts causes overheating, which can cause thermal runaway. Regular maintenance is necessary to ensure continued proper functioning.

Oil testing has long been recognised as an important tool for detecting incipient faults in the main tanks of transformers and is being applied to load tap changers. Some of the advantages of oil testing are:

- can usually be performed while equipment remains in service
- can detect a wide range of problems in the early stages
- can be used to ascertain a reasonable sense of the severity of the problem
- has been shown to be very cost effective

Oil testing is used to provide one of the most important early warning diagnostics for on-load tap changers and, because of its effectiveness, has made condition-based maintenance a reality.

Abstract: Dissolved gas analysis (DGA) has been applied successfully for many years to non-current switching oil-filled power equipment. The application of DGA to OLTCs has both similarities and differences to the use of DGA in other oil-filled power equipment. It is similar in that the same processes produce the same gases. However, in terms of gas production, OLTCs are far more complex than transformers. OLTCs may or may not produce all of the so-called 'fault gases' in normal operation and the gases that are produced may or may not be lost through venting. The first applications of DGA to evaluate the condition of an OLTC were based on experiences with transformers. Threshold limits were developed for the gases produced by overheating, both individually and in combination. Many factors such as design, operation, ventilation, and on-line filtration affect gas levels. Consequently, this gas-threshold approach offered limited success, but proved the potential usefulness of fluid testing for OLTC condition assessment. Since gas data alone cannot provide sufficient information to fully assess OLTC condition, new approaches were required for OLTC evaluations. The search for an effective new approach led to the development of Condition Codes, which provide a condition assessment of the load path components. In addition to revealing useful information for the maintenance of insulating

fluid, fluid assessment tests are used in conjunction with OLTC gas data to provide diagnostic information about the condition of OLTCs. Keeping the oil free of water, arc decomposition products and other contaminants is essential for proper operation of the OLTC. Particle profiling provides important information about the deterioration of materials that result in particle production. This includes information about in-service processes such as fluid degradation, contact deterioration and mechanical wear of moving parts and rust formation. Two of the most important fluid degradation processes to be evaluated are charring of the oil and coke formation.

Table 1 shows the gas-producing processes that occur in oil-filled electrical equipment. The gases that are produced by these processes are listed in Table 2. Recognition of these differences between normal and abnormal gassing patterns paved the way to diagnostic assessment of OLTCs.

Table 1 – Gas-producing process		
Equipment	**Normal**	**Abnormal**
Transformers	Heating	Excessive heating, partial discharge and arcing
OLTCs	Arcing	Excessive heating and partial discharge

Table 2	
Gases	**Indication**
Hydrogen	Partial discharge, heating arcing
Ethylene, Ethane, Methane	"Hot metal" gases (heating)
Acetylene	Arcing
Carbon oxides	Cellulose insulation degradation

DGA and other non-invasive tests can be combined to assess the OLTC's condition. Diagnostic programmes have been successfully developed to achieve the goal of condition-based maintenance with the consequent saving in costs.

Table 3 – Diagnostic tools		
Diagnostic tool	**Problem detected**	**Result**
DGA	Coking, contact misalignment	Overheating (thermal run-way)
Oil quality	Coking, contact wear, change in arcing characteristics, oil sludging	Conducting particles in oil, sludge
Metal analysis	Contact wear, misalignment	Contact wear

NON-INVASIVE TESTS FOR OLTCs

Dielectric breakdown voltage: the oil in an OLTC should maintain a minimum dielectric breakdown voltage. In recent years on-line filters have been used for compartments containing arcing contacts in oil to better maintain the dielectric breakdown strength of the insulating materials. This approach has been effective in pushing out maintenance cycles and reducing the rate of contact wear. The dielectric breakdown voltage is a function of the relative saturation of water in oil and the amount, size, and type (conductivity) of particles.

Water Content: excessive water reduces the dielectric breakdown strength of the oil and can accelerate the aging of the contacts.

Neutralisation number: As oils and cellulosic materials age, they will deteriorate and form aging by-products, including acids. Eventually the aging by-products will begin to polymerize and form sludges. Increasing acidity can be used as a guide to the aging rate of the oil. When high values are reached, the oil should be replaced or reclaimed. Acid by-products, particularly in the presence of water, are corrosive.

Total metals in oil: The metals test, consisting of both particulate metals and those dissolved in the oil, is an extremely meaningful test. It provides an indication of the amount of material that has been worn or sublimated from the moving and/or stationary contacts and is now present in the oil. It also provides a quantitative analysis as to composition of the metals found in the oil.

Particle count and qualitative analysis: The total number of particles by size groupings is used to detect abnormal quantities of by-products and wear materials. The ratio(s) of the size groupings provides information as to the extent that a detrimental condition has progressed.

DGA DIAGNOSTICS

It is undisputed that DGA plays a primary diagnostic role. The interpretation protocol for applying DGA is empirical in nature. In the case of OLTCs it is generally accepted that fault gas interpretation will be most useful if it is model specific. Individual gas concentrations-based diagnostics for OLTCs are not useful as they are operation count-and breathing configuration-dependent. DGA ratios of fault gases are fairly independent of operation count. The various gas ratios are excellent diagnostic tools. Table 4 lists the gas ratios proposed by Weidmann-ACTI (F. Jakob, K. Jakob, S. Jones)

Table 4 – Diagnostic gas ratios			
Heating to arcing ratios			
Ratio 1	Ratio 2	Ratio 3	Ratio 4
Temperature-dependent ratios			
Ratio 5		Ratio 6	

The primary test for OLTC diagnostics and condition assessment is that of dissolved gas-in-oil, as this detects most of the problems. There are three main types of OLTCs:
- reactive with arcing contacts in oil,
- resistive with arcing contacts in oil and
- arcing contacts in a vacuum bottle.

There should be differences in the gassing behaviour between resistive and reactive types, as the shorter time of arc extinction of the resistive type (5-6 mins after contact separation) should lower the concentrations of gases generated. However, the gassing behaviour of different models of OLTCs is so different that generic rules for reactive and resistive OLTCs are not adequate.

The primary diagnostic gases used to develop condition codes are methane, ethylene and acetylene. In addition, three ratios are used:
- ethylene/acetylene: distinguishes between thermal and electrical discharge activity in oil
- methane/acetylene: distinguishes between thermal and electrical discharge activity in oil and can also detect partial discharge activity as a predominant gassing pattern. For example, localised overheating of contacts or the reversing switch will generally show increasing combustible gas generation with ratios of gassing going from an arcing pattern to characteristics of high temperature overheating of oil. Excessive arcing between contacts is most likely to develop high gas concentrations until the later stages when heating occurs (causing the combustible gas ratios to change). Examples of causes of overheating include:
  - excessive contact resistance due to the formation of organic films and carbon deposits
  - metal fatigue causing poor contact pressure
  - loss of direct contact surface area from misalignment or loss of contact material

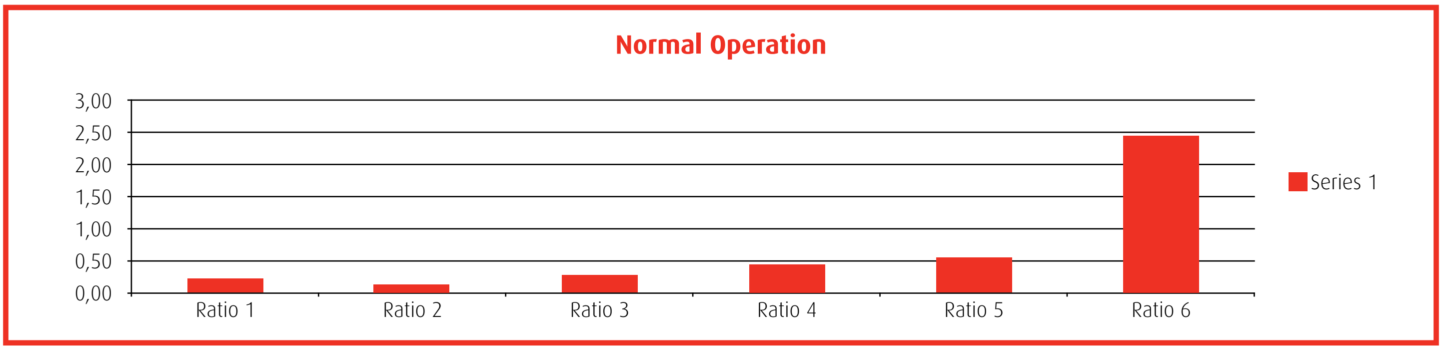
Excessive combustible gas build-up can result when the vent becomes plugged. This eventually leads to low oxygen content as it is consumed in oxidation reactions and is not replenished. Typically, the ratios will remain normal unless another problem is present at the same time. Various other thermal and electrical problems can also be detected depending upon the model of OLTC.

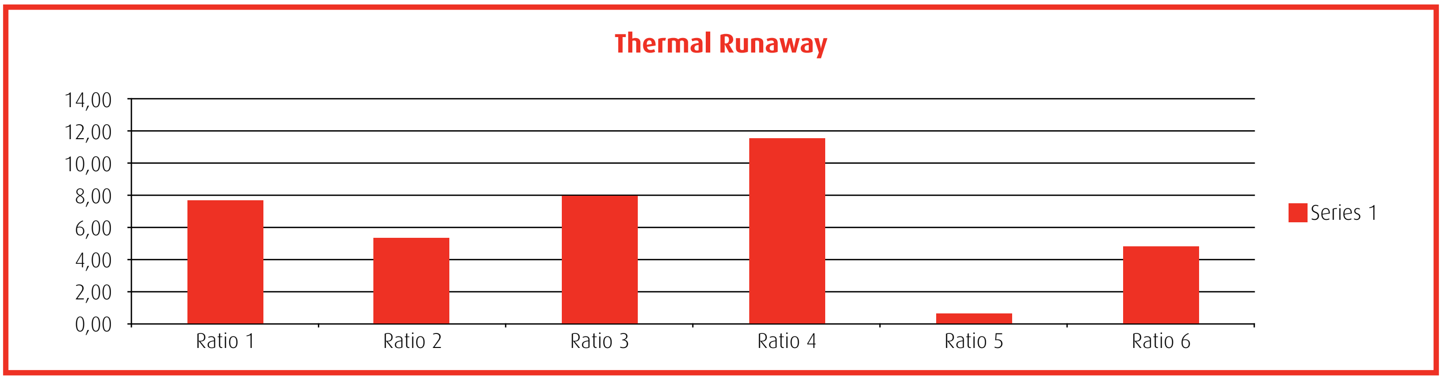
NEW DGA INTERPRETATION SCHEME

In an attempt to improve the understanding of the significance of DGA results, the 'Kohonen net' cluster analysis technique has been relatively successful in grouping together DGA results of an apparently similar significance and identifying when a result appears to move to a different state. Although such techniques can be argued to provide a better basis for identifying an unusual condition than the purely statistical approach, they still rely very much on the human expert to ascribe some significance to the clusters identified.

The new approach proposed makes use of the relative proportions of the six combustible gases H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2, which are displayed as a bar chart to illustrate the gas signature. The novel aspect of the approach proposed here is that this method is used to investigate and illustrate the clear difference that exists between 'normal' and 'abnormal' results.

The graphical plotting of these ratios gives a clear indication of a heating problem (thermal runaway) when compared to the normal arcing process.

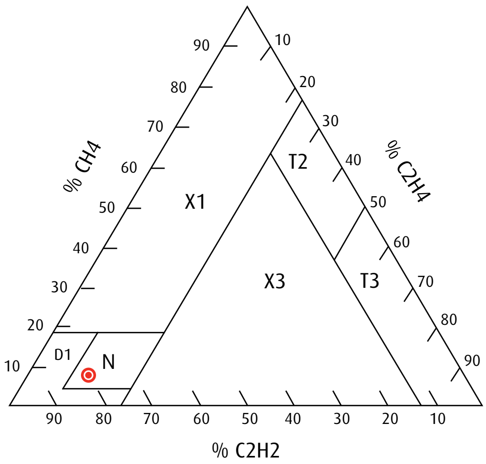


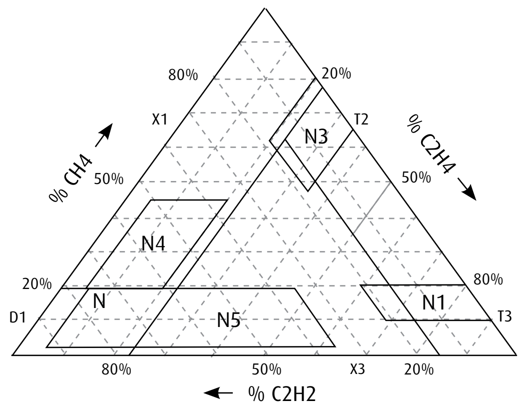


DUVAL TRIANGLE FOR THE INTERPRETATION OF DGA IN OLTCs

The Duval Triangle using CH_4, C_2H_4 AND C_2H_2 gases in a single graphical representation has been developed for tap changers, the basic Duval Triangle can be used to detect faults in compartment-type OLTCs.

When DGA points move with time from the normal to a fault zone, this means a fault is appearing. What makes the use of DGA in OLTCs different from its use in transformers is that during the normal switching operation of OLTCs, arcs in oil or hot spots in various OLTC components are produced, generating gases such as C_2H_2 and C_2H_4 which may interfere with the detection of abnormal faults. The 'normal' gas formation of OLTCs must therefore be identified first as precisely as possible, in order to use DGA for the detection of faults in OLTCs. Triangle 2 has been developed to distinguish between normal and abnormal gas formation in OLTCs of the compartment and in-tank resistive-type OLTCs that, without any fault, generate large amounts of heating gas, especially ethylene.





Fault Zones:

N – Normal operations

T2 – Thermal faults: 300 < T < 700˚C

T3 – Thermal faults T> 700˚C

X1 – Fault T3/T2 in progress

X3 - Abnormal arcing D2

D1 – Abnormal arcing D1

The following three case studies illustrate how DGA was used to successfully predicted imminent failure of the OLTCs, which were then removed from service and repaired before catastrophic failure occurred.

CASE 1

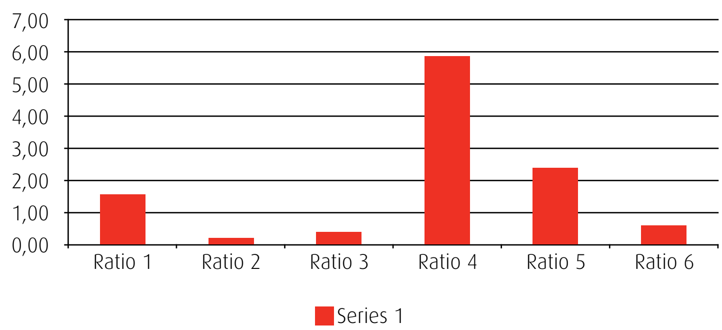
Client: Mozal Smelter
Region: MOZAMBIQUE
District: Boane
Substation: 132kV AIS, AUX NO.2
Transformer No: 7100-TFP-002, T/C
Serial No: AID69222T21TC
Sample Point: TAP CHANGER

Sample Date: 05/05/2004
Analyses Date: 21/05/2004
Primary Voltage: 132kV
Secondary Voltage: 22kV
VA Rating: 31.5 MVA
Vector Group: Dyn1
Impedence: 11.92%

Tap Changer: On Load
Make: M.R.G.
Year Manufactured: 1999
Conservator: Yes
Breather Size: SA2
Oil Volume Litres: 400
Report No: MOZAL-8988

DISSOLVED GAS (DGA) VPM@NTP		
Hydrogen	H_2	7 465
Oxygen	O_2	1 165
Nitrogen	N_2	73 197
Methane	CH_4	690
Carbon Monoxide	CO	128
Carbon Dioxide	CO_2	66
Ethylene	C_2H_4	727
Ethane	C_2H_6	1 468
Acetylene	C_2H_2	390
Total % Gas		**8.48**
Total Gas Combustibles		**10 868**

7100-TFP-002, OLTC



REPORT: The DGA indicates a partial discharge of low energy (Corona).
The Ratio profile indicates abnormal operation. *Note: this is not normal for an OLTC.*

RECOMMENDED: Contact manufacturer.

RESULTS OF INVESTIGATION: The amount and ratios of gases revealed the approaching failure. The unit was serviced, reversing switch contacts were cleaned, tightened and placed back in service. The DGA now shows normal operation of the OLTC.

CASE 2

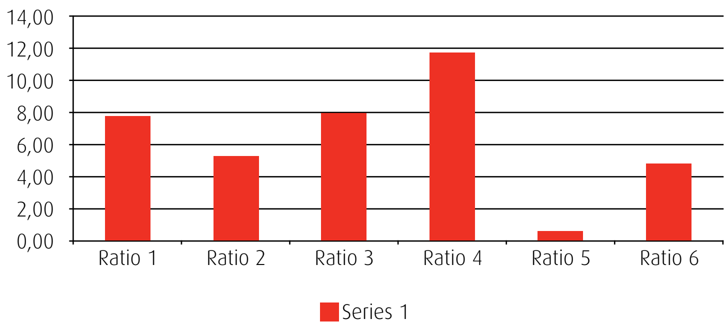
Client: Durban Electricity
Region: KZN
District: Durban
Substation: Hillcrest
Transformer No: T 1A, T/C
Serial No: 2206328
Sample Point: TAP CHANGER

Sample Date: 09/12/2008
Analyses Date: 10/12/2008
Primary Voltage: 132kV
Secondary Voltage: 11kV
VA Rating: 30 MVA
Vector Group: YNyn0

Impedence:
Tap Changer: On Load
Make: ASEA
Year Manufactured: 1975
Conservator: Yes

DISSOLVED GAS (DGA) VPM@NTP		
Hydrogen	H_2	797
Oxygen	O_2	13 257
Nitrogen	N_2	32 073
Methane	CH_4	**4 145**
Carbon Monoxide	CO	886
Carbon Dioxide	CO_2	5 068
Ethylene	C_2H_4	**13 797**
Ethane	C_2H_6	**2 823**
Acetylene	C_2H_2	1 814
Total % Gas		**7.46**
Total Gas Combustibles		**24 242**

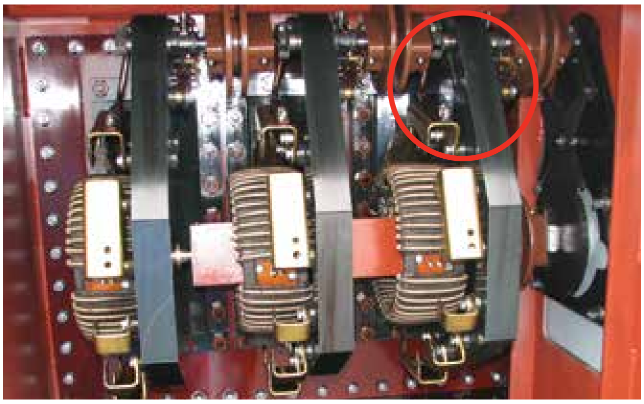
Hillcrest T1A OLTC

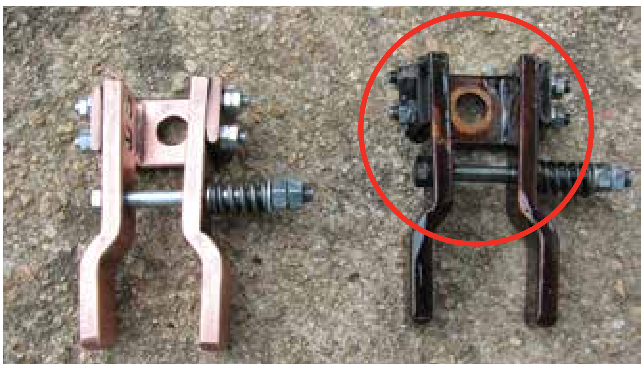


REPORT: **The DGA indicates a thermal fault (hot metal gases – thermal runaway).**
See diagnosis ratios. *Note: the sample was taken following a fault trip. (Buchholz surge relay operation on the OLTC).*

RECOMMENDED: Remove from service for inspection/repairs. Resample after treatment.

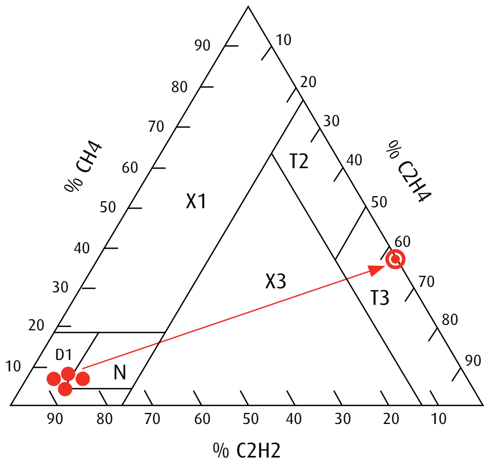
RESULTS OF INVESTIGATION: The internal investigation found severe burning and coking on the forward/reversing moving arm contacts and springs of the red phase. The fixed contacts were coked and slightly burnt. The other phase contacts were also coked and, with time, would have developed into a similar condition. All the forward/reverse fixed and moving contacts were replaced.

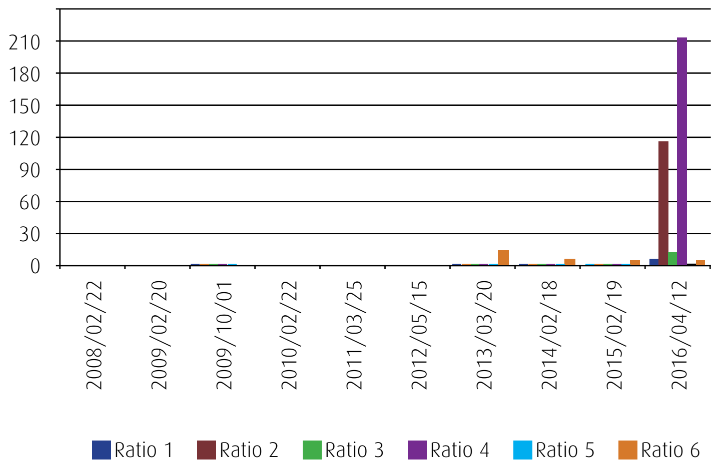




CASE 3

Client: SASOL Synfuels Generatot Step Transformer (GSU)
Manufacturer of OLTC: ASEA 132kV: 60MVA
Year of Manufacture: 1981
Diagnosis: Thermal Runaway T>700˚C /Burnt Contacts





Fault Zones:

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Date	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	Ratio 1	Ratio 2	Ratio 3	Ratio 4	Ratio 5	Ratio 6	Sensestam Ratio	Diagnosis
2016-04-12	1896	7533	238	1226	12329	107	6.16	115.22	11.32	211.93	0.37	4.38	211.93	Overheating – contact the manufacturer
2015-02-19	34	6	22	546	6	66	0.06	0.09	0.16	0.24	0.67	1.50	0.24	No overheating present
2014-02-18	46	9	15	509	13	88	0.10	0.15	0.18	0.27	0.22	6.50	0.27	No overheating present
2013-03-20	0	10	44	1133	13	120	0.11	0.11	0.20	0.20	0.10	13.00	0.20	No overheating present
2009-10-01	150	10	44	1207	13	115	0.05	0.11	0.09	0.20	0.00		0.20	No overheating present

RESULTS OF INVESTIGATION: This case provides an example where the DGA was an indicator of a thermal runaway condition prior to failure.

Note: The amount and ratios of gases revealed the approaching failure. The problem in this unit was found to be a burnt contact switch.

Remedial action taken avoided catastrophic failure, which was estimated at two weeks. If left undetected, the result would have been between six weeks and six months of forced outage.

Savings can be estimated in millions of Rands due the strategic importance of this GSU (generator step-up unit).

CONFIRMATION AND COMPLEMENTARY TESTS

There are several non-oil tests that have been employed to confirm or identify OLTC problems. These include the following:

Infrared thermography and temperature differential: a frequently-used method to detect or confirm overheating of contacts or the reversing switch in OLTCs is to determine the temperature difference between the main tank and the OLTC. Normally, the main tank should be operating at a higher temperature than the OLTC compartment except for the occasional transient, such as when the pumps initially come on to cool the main insulation. As thermal problems develop in the OLTC compartment, the oil temperature will consistently be higher than the main tank. This difference in temperature can be detected using continuous temperature monitors mounted to the tank wall or by periodic inspections using infrared thermography.

Electrical tests: there are several electrical tests that can be used to confirm or help identify the source of OLTC problems before entering for visual inspection.

- Exciting current tests on all OLTC tap positions can be used to detect shorted turns and core problems in the preventive autotransformer, contact problems and connection problems in the preventive autotransformer or in taps.
- Turns ratio can detect shorted turns in the preventive autotransformer.
- Power factor tests are used to detect insulation deterioration such as from moisture and partial discharge activity, including tracking and carbonisation of solid insulation structures.
- Contact resistance is used to detect excessive contact wear, poor contact pressure, and coking and polymeric films on contact surfaces.
- Sweep Frequency Response Analysis (SFRA) and leakage reactance (short circuit impedance) are both used to detect winding movement or deformation and contact problems.
- Tap changer Diverter Resistor and Contact Analysis provides a means for condition assessment of tap changers using dynamic contact resistance measurement techniques. A signal is injected into the phase under test with the secondary and tertiary windings shorted. The tap changer is tapped through its sequence and a trace is produced of the complete sequence. The detail of each tap can be viewed, allowing the timing of the transition to be measured. The test results provide the necessary information to establish the state of the tap changer to make planned decisions or take corrective actions minimising the need for intrusive inspections.

Acoustic and vibration analysis: some investigators have developed a database of OLTC signatures using acoustic analysis to complement diagnostic programs for OLTCs.

The advantages of the Tap Changer Analysis programme are:

- Units that require maintenance are identified.
- Units that do not currently require maintenance are identified
- Maintenance activities can be better focused.
- Operators and planners can assess loading capabilities.
- Failures and collateral damage to transformers can be reduced.
- Reliability is enhanced.
- Costs are reduced.
- Safety is not compromised.

Percentage savings in maintenance						
		Fixed – year maintenance interval (years)				
		2	3	4	5	6
% of units	12%	76	64	52	40	32
Requiring	14%	72	58	44	30	20
Maintenance	17%	66	49	32	15	20
Based on	20%	60	40	20		
Condition code	25%	50	25			

Percent savings are based on a comparison of the percentage of units requiring maintenance as given by the condition code versus the number that would be maintained on a fixed-time interval.

CONCLUSION

The ability of utilities and other power transformer operators to convert from time-based maintenance to condition-based maintenance for on-load tap changers has been greatly enhanced by the advancement of oil diagnostic testing. These tests have gained acceptance in the industry and will be standard practice in the near future. We have found that once oil diagnostics programmes are started for OLTCs, problems that were not detected by other methods are revealed, and there is acceptance of this approach. After using oil diagnostics for all the OLTCs in a system, the number of problems found the second time around is reduced, showing the effectiveness of the programme.

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