ANALYSIS OF FAILED ESKOM TRANSMISSION TRANSFORMERS WITH DGA SIGNATURE PATTERNS

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ABSTRACT

This paper presents a literature review on oil paper insulation test techniques and the results from a DGA study into failed Eskom Transmission transformers to identify typical failure signature patterns

The literature review on oil paper insulation in power transformers details the current test techniques as well as new techniques. The tests include those of DGA, oil quality and paper quality. The technique of using DGA is a very well established method to detect faults on transformers.

Historical DGA of failed units was performed to identify typical signature patterns of the failures. The DGA failure signatures were divided into 3 categories, namely dielectric, thermal and overloading. The trends of the DGA signatures proved to be a key component in the detection of these faults.

INTRODUCTION

Transformers are the most expensive piece of equipment in the substation and require a specialised skill to deal with. The safe and optimum use of transformers is of paramount importance in the integrity of the system. Fault conditions in transformers produce gases dissolved in the oil. The knowledge and quality of the insulation is a key factor in determining the state of the transformer.

The majority of transformer failures worldwide are due to internal winding faults, faulty load tap changers and failed winding accessories which are difficult to detect due to the complex construction of the transformer. Methodologies and techniques have been researched and published over the years to provide assistance in condition assessment of transformers. Eskom has embarked on this research project to be able to better predict impending transformer failures and also the suitable maintenance intervention that can be applied.

The literature review on oil paper insulation in power transformers details the current test techniques as well as new techniques. The tests include those of DGA, oil quality and paper quality.

The techniques are based on the following guidelines:
1) Oil condition based on DGA: IEC 60599, California State University Sacramento (CSUS), Duval's Triangle, IEEE STD C57.104-1991, Roger's ratios, and Dornenburg ratios;
2) Oil Quality based on dielectric strength, neutralization value, interfacial tension, moisture content, tan delta and quality index system; and
3) Paper condition based on moisture in oil, DGA and furan analysis.

Historical DGA of failed units was performed to identify typical signature patterns of the failures. The DGA failure signatures were divided into 3 categories, namely dielectric, thermal and overloading. The trends of the DGA signatures proved to be a key component in the detection of these faults.

REVIEW OF EXISTING DGA METHODS

(1) IEC DGA Method

DGA is one of the most widely used diagnostic tools for detecting and evaluating faults in electrical equipment. However, interpretation of DGA results is often complex and experience is a necessity. The IEC guide gives information for facilitating this interpretation. Interpretation schemes are based on observations made after inspection of a large number of faulty oil-filled equipment in service and concentrations levels deduced from analyses collected worldwide.

Table 1 below details the advantages, disadvantages as well as comments for the IEC method. It can be seen that the most vital short coming of these techniques are that the transformer history is not considered and that multiple faults are not diagnosed.

Table 1: IEC DGA Method

Method: IEC		
For	**Against**	**Comments**
Detailed diagnosis	Number of possible faults – not specific	Derived from Rogers Ratios. Constant disagreement in terms of the concentration of gases for normal transformers.
Most extensively used	Inability to diagnose multiple faults	
Under constant review by IEC	Produces codes that have no diagnosis	
Taken into consideration CO/CO_2 for paper health	Concentration of gases for normal transformers is found to be subjective – typically Hydrogen and Acetylene	
Typical in service gas levels are given for normal transformers	Does not consider transformer history	
Considers rate of gas formation per day and year, with alarm values	Cannot identify stray gassing	
Gives basic recommendations if gas levels are high	Does not provide a way to track the fault progression over time	

(2) IEEE STD C57.104-1991 DGA Method

The scope of the guide is to give the user the background into gas generation in transformers in terms of general theory. It further demonstrates the use of different techniques to interpret gases generated from oil filled in service transformers. Limitations within the guide are also highlighted. This guide is an advisory document. However, it provides guidance on specific methods and procedures to assist the transformer operator in deciding on the status and continued operation of a transformer that exhibits combustible gas formation. Table 2 below details the advantages, disadvantages as well as comments for the IEEE method. It can be seen that the most vital short coming of these techniques are that the transformer history is not considered and that multiple faults are not diagnosed.

Table 2: **IEEE** STD C57.104-1991 DGA Method

For	**Against**	**Comments**
Under constant review by IEEE	Inability to diagnosis multiple faults	Used extensively in the US however gaining popularity in the UK. SD Myers has modified the key gas DGA signatures
Takes into consideration CO/CO_2 for paper health	Cannot identify stray gassing	
Well defined application layout	Does not consider transformer history	
Typical gas levels are given to identify transformer condition	Does not provide a way to track the fault progression over time	
Takes into consideration dissolved combustible gas in oil and combustible gas in gas space		
Gives recommendations based on combustible gas daily rates		
Uses three methods for diagnosis of faults Key gas, Rogers Ratios and Dornenburg Ratios		

(3) Rogers Ratios

RR Rogers developed this quantitative method in 1974 from about 10 000 DGA samples from the UK. The method makes use of four ratios to be matched against 12 possible diagnostic cases.

Table 3: Rogers Ratio DGA method

Method: Roger's Ratio		
For	**Against**	**Comments**
Uses four ratios	Inability to diagnose multiple faults	Developed from about 10000 gas samples. The "0000" code that identifies a normal transformer this is encountered less often than might reasonably be expected for populations which contain mainly transformers without any known faults. Major reason for the previous observation, the method becomes less reliable at low gas concentrations
Detailed diagnosis with 12 cases	Cannot identify stray gassing	
Does not need gasses to exceed a minimum level	Does not consider transformer history	
Identifies a normal operating transformer	Does not provide a way to track the fault progression over time	
	Does take into consideration CO/CO_2 for paper health	
	Produces codes that have no diagnosis	
	Developed from free breathing transformers	

(4) Dornenberg Ratio

Table 4: Dornenberg Ratio Method

Method: Dornenberg		
For	**Against**	**Comments**
Uses four ratios Clear difference between gases extracted from oil and gas spaces	Inability to diagnose multiple faults	The concentration limits for each gas have been modified by IEEE
	Cannot identify stray gassing	
	Does not consider transformer history	
	Does not provide a way to track the fault progression over time	
	Does taken into consideration CO/CO_2 for paper health	
	Produces codes that have no diagnosis	
	Limited diagnosis	

(5) Duval Triangle

Table 5: Duval Triangle Method

Method: Duval		
For	**Against**	**Comments**
Interpretation is simplified by a graphical layout	Does not consider H_2 in the ratios	The greatest disadvantage is that H_2 is not included in the ratios used by Duval. H_2 has been proven to be a key indicator for dielectric faults.
Not affected by low gas levels	Inability to diagnose multiple faults	
Under constant review	Cannot identify stray gassing	
	Does not consider transformer history	
	Does not provide a way to track the fault progression over time	
	Does not identify a normal transformer	

	Does taken into consideration CO/CO_2 for paper health	

(6) **California State University Sacramento**

Table 6: CSUS Method

Method: CSUS		
For	**Against**	**Comments**
Simple with no calculations required.	Inability to diagnose multiple faults	Not widely used.
Details limits for normal and abnormal conditions	Cannot identify stray gassing	
	Does not consider transformer history	
	Does not provide a way to track the fault progression over time	
	Limited diagnosis	

REVIEW OF NEW DGA DIAGNOSTIC METHODS

a) Doble DGA Scoring System

The Doble method of interpreting DGA results is seen to tackle the main weakness of existing schemes i.e. the difficulty of defining a normal condition. A simple scoring system based on results from known problems is used to provide a consistent and objective assessment of the seriousness of results, to improve the effectiveness of life management decisions.

The new approach makes use of the Key Gas Method of presenting DGA results used by IEEE. The relative proportions of the six combustible gases CO, H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 are displayed as a bar chart to illustrate the gas signature. This method is used to investigate and illustrate the clear difference that exists between 'normal and 'abnormal' results. By contrast, in the IEEE Guide four examples of 'faults' are given, but there is no guidance on what a 'normal' result would look like.

In this scheme, DGA results for normal transmission and generator transformers would be expected to return a score of no more than about 30, whereas a core circulating current would rate about 60 and more serious problems would score around 100 or higher. The scoring algorithm used is a product of both 'quality' (dependent on the gas signature and ratios) and 'strength' (depending on absolute levels) functions, but is strongly influenced by the former.

Because of this the DGA score will usually increase if the absolute levels of the key diagnostic gases increase, but the most important factor resulting in an increase in score will be a change in the gas signature towards what is perceived as a more serious case.

b) The Vector Algorithm

The Vector Algorithm is based on the chemical and physical principles of the Rogers Ratios and Duval Triangle. All three methods are consistent with Halstead's thermodynamic reasoning that with increasing temperature the hydrocarbon gas with maximum rate of evolution would in turn be methane, ethane, ethylene, and acetylene. The other gases usually present in an oil sample are notably hydrogen, carbon monoxide, carbon dioxide, moisture and air. The levels and proportions of all of these gases provide meaningful information on the operating conditions of the oil-impregnated insulation.

REVIEW OF LATEST PAPER DEGRADATION DIAGNOSTIC METHODS

a) Sugars

Studies on paper decomposition showed that levoglucosan plays a key role in the thermal degradation of paper and that this compound could be a key intermediate product in the degradation of cellulose which could lead directly to the formation of furanic compounds.

b) Organic Acids

The presence of various organic acids in oil appears to be caused by the oxidation of oil. Studies also show that they could also be formed by reactions following hydrolysis.

c) Volatile Compounds

Acetone which is formed in negligible quantities in oil is highly soluble in oil. One can observe the molecules appearance in oil well before that of 2 FAL, and it was noted that a good correlation exits between its development over time and the papers DP.

d) Dielectric Diagnosis of Solid Insulation

The measurement of the dielectric response can be measured in several ways:

1) Measurement of polarization and depolarization currents after application of stepped DC voltages, called polarization and depolarization current measurements.
2) Measurement of currents and phase lag using a swept frequency sine wave voltage, from which the capacitance and tan delta can be calculated. This is called frequency domain spectroscopy.
3) Measuring the voltage increase on an ungrounded transformer after it has been polarized for a certain time, the so called return voltage measurement.

It is possible to separate the influence of the oil and solid insulation in a response measurement. The oil has a frequency independent permittivity and a conductivity that depends on composition, contamination and temperature. The conductivity can either be measured directly or read out from response measurements to either short times in the time domain measurement, or high frequencies in the frequency measurement. The response of the solid is found for the longer relaxation times in a time domain measurements or for lower frequencies in the frequency domain measurements. From the response measurements at different temperatures one can design a response curve for a pressboard. This master curve varies with water content.

e) Furanic Compounds

The loss of the mechanical properties of paper insulation is linked to a decrease in its degree of polymerization and changes in some furanic compounds. It can be shown that each time three cellulose chains are broken; one 2-furfural (2FAL) molecule is generated.

However, the relationship between the 2FAL and the average degree of polymerization of cellulosic insulation is dependent on the operating conditions. Although an analysis of furanic compounds combined with a DGA analysis presents a certain level of reliability, it is difficult to use their threshold values or ratios for diagnostic purposes due to a lack of knowledge of how these compounds are formed and evolve over time.

Research shows that furanic compounds are influenced by:

1) Humidity and type of the paper.
2) Less influenced by temperature unless it is in conjunction with acidic oil.
3) Different for each furanic compound.

Furanic compounds give information about paper degradation, but this analysis has its limitations. Experience shows that these compounds are dependent on the transformer’s operating conditions, and the effects of water, oxygen and acidity. In addition, the type and quality of oil influence not only the speed of ageing and the production of furanic compounds but also their quantity, stability and solubility in oil. Due to these limitations, it is not possible to predict the remaining life of a transformer, based solely on the analysis of furanic compounds.

DGA SIGNATURE ANALYSIS ON FAILED ESKOM TRANSFORMERS

The DGA signature analysis on failed units documents the DGA trending for transformers that have failed in service as a result of internal faults. The objective is to use condition data to predict failures. Case Studies of 50 transformers that have failed on Eskom's transmission grid were analysed based on their DGA history. The DGA trends leading up to the failure were analysed carefully to identify possible early warning indicators of imminent failure. Case studies of 5 such analysis is given below.

Dielectric Fault

The DGA signature below indicates a dielectric fault. The trend of the signature shows **significant levels of hydrogen and methane** in the development stages of the fault. However there is an increase in the ethylene levels just before failure. This signature was compared to other dielectric fault that showed lower levels of methane. Sparking of winding clamping bolts show low levels of methane and hydrogen when compared to acetylene.

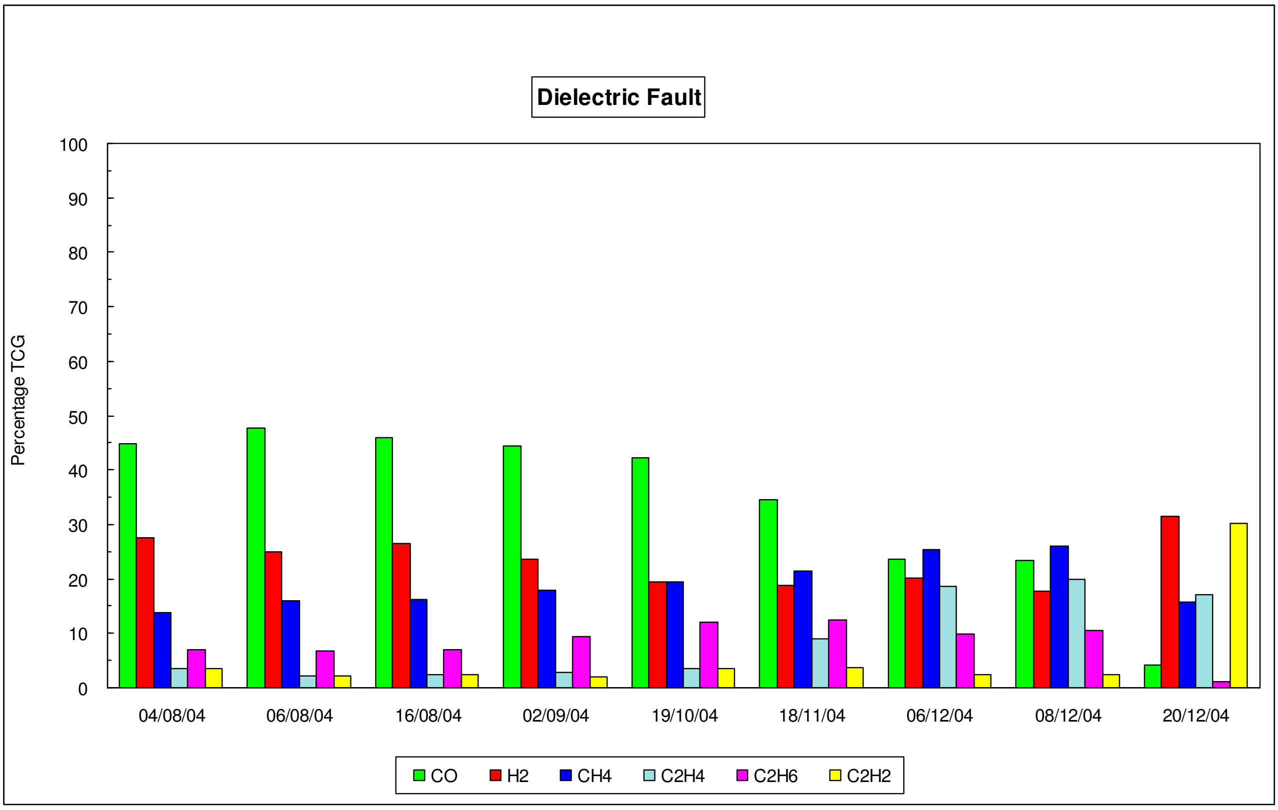

Figure 1: Dielectric Fault

Localised Thermal Fault

The localised thermal faults are clearly divided into two types of faults: a bare metal type fault and a fault covered conductor fault.

Figure 2 below is a DGA signature for a localised thermal fault of a bare metal type fault. Such as circulation currents between core/frame and earth or an overheating selector contact. The signature shows high levels of ethylene over methane and ethane.

Figure 3 below is a DGA signature for a localised thermal fault of a covered conductor fault. This is typical fault that involves the windings. The clear difference is the higher levels of methane and hydrogen.

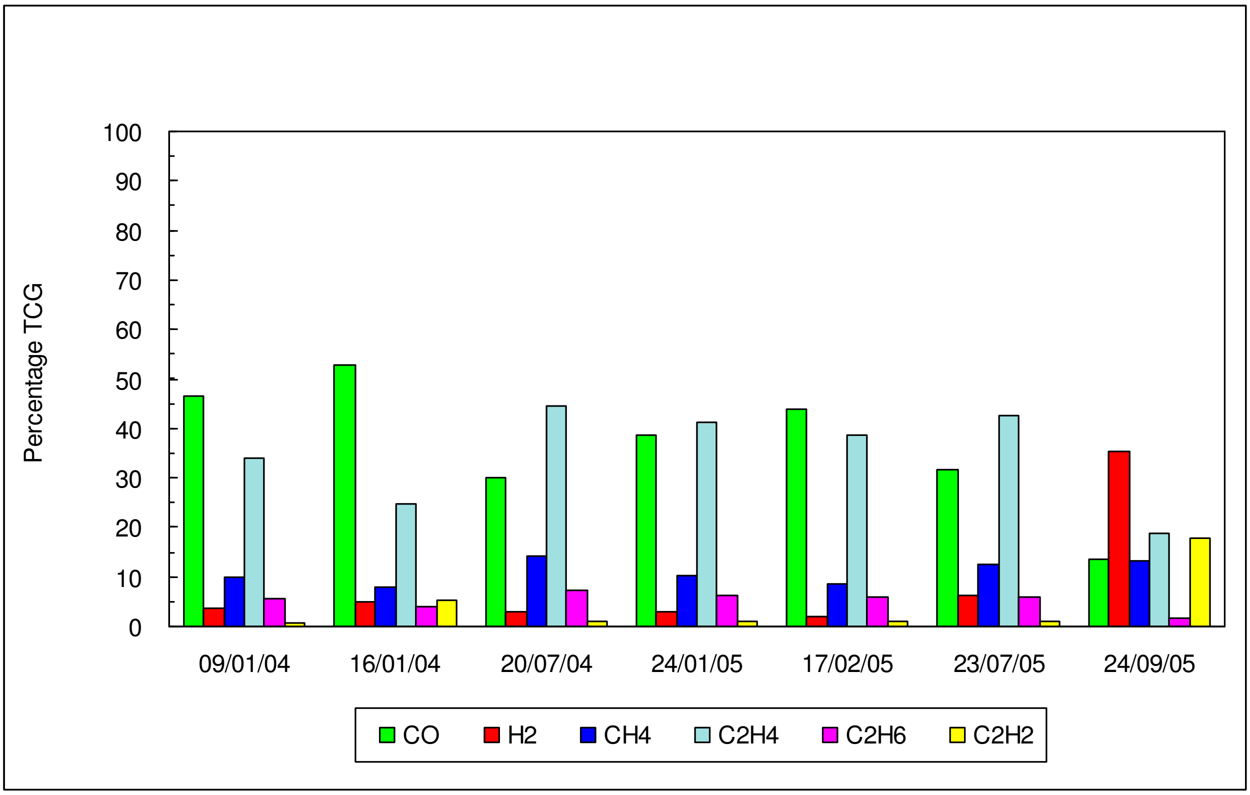

Figure 2: Bare metal type fault

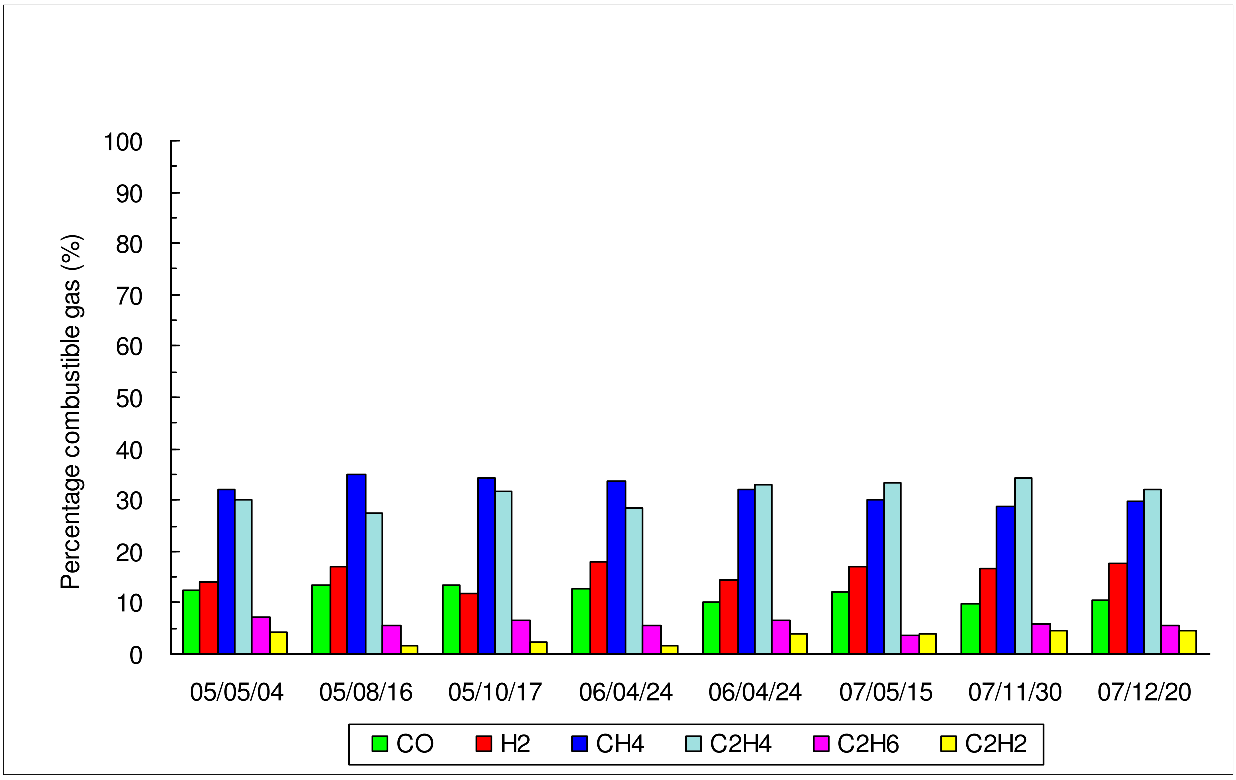

Figure 3: Covered Conductor fault

Overheating Transformers

The DGA signatures for load transformers show **significant levels of methane and ethane**. However, the levels of methane when compared to ethane can be equal or in some cases ethane is significantly higher than methane or methane levels are higher than ethane. The effect of an **overheating transformer could be from loading, clogged cooling ducts, incorrect operation of cooling systems (problems with fans and insufficient radiators).**

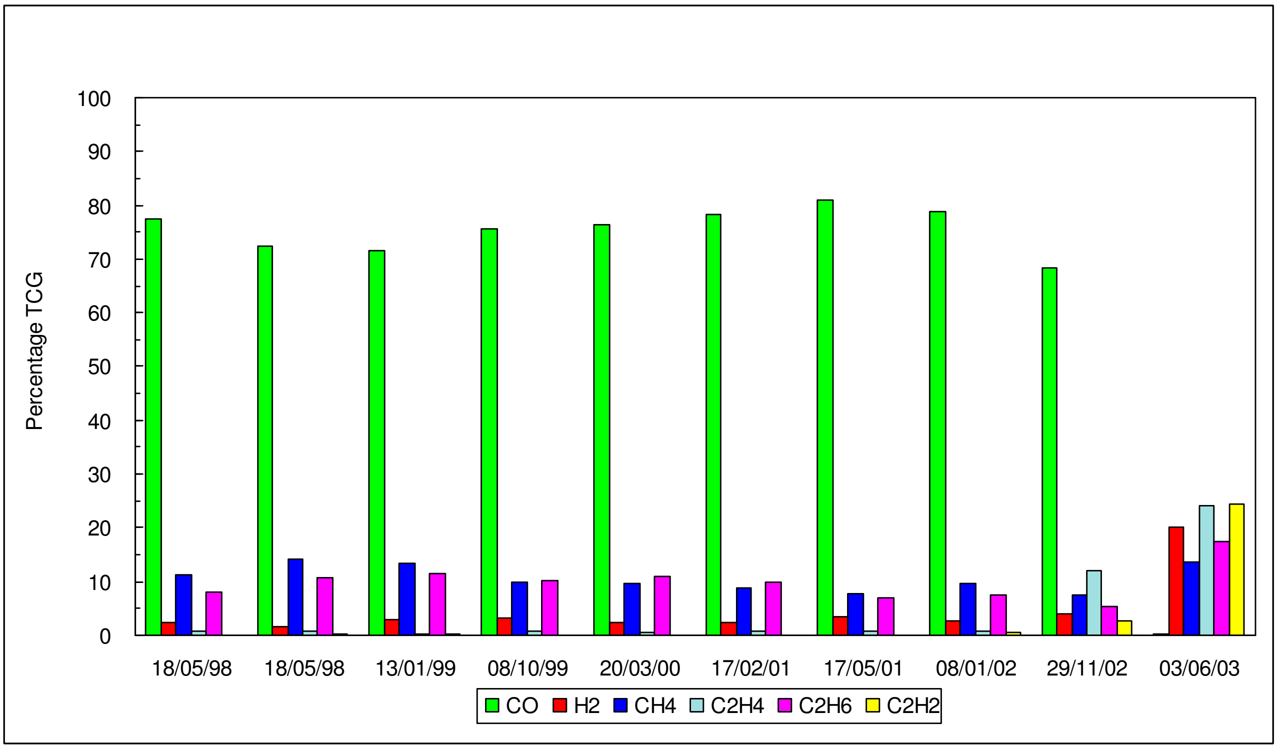

Figure 4: Overheating Transformer

FINDINGS

(1) The DGA methods covered were the IEC 60599, CSUS, Duval Triangle, IEEE Std C57.104-1991, Roger's Ratio, Dornenburg Ratios. These cover fault types, basic gas ratios, gas concentrations and rates of gas production. There are a number of **shortcoming and limitations**. The key shortcomings are the inability to detect multiple faults, not provide a way to track the fault progression, and they do not consider the transformer's history.

(2) **New techniques such as the Doble DGA Scoring System and the Vector algorithm eliminate some of shortcomings within the existing DGA methods**. The Doble DGA Scoring System has the ability to track the fault progression over different test samples by assigning a numerical score to each test sample. It further uses the Key Gas method to identify the fault type. The method also has the ability to clearly identify a normally operating transformer. DGA signatures are also provided on typical fault types that can be used for comparison purposes to identify fault types. The Vector Algorithm has the ability to detect multiple faults suffered by transformers. The method is based loosely around the IEEE method but employs an algorithm to provide a very high degree of selectivity between different fault types.

(3) **Furan analysis is an invaluable tool for establishing the aged state of the paper insulation**. Research has shown that a number of factors have a significant influence on the amount of furanic compound formed. The other point of controversy is that the relationship between 2-furfural and the Chendong equation. Experts claim that the DP value of 200 is an excellent prediction of end of life. However, DP's of 350-400 would be expected to have considerable life left. The analysis of failed transformers in the UK has shown that the Chendong equation is not a good fit for the data obtained.

There are considerable doubts about the reliability of laboratory derived correlations for ageing evaluation, which simply derive estimated DP from a furan concentration. A new agreed approach is a simple composite evaluation which takes into account the following factors: Design, 2FAL, rate of change of 2FAL, operating temperature, and CO level.

(4) Traditionally the **CO_2/CO ratio is supposed to be the key indicator of normal or abnormal ageing**, but UK experience with mainly free breathing transformers is that CO_2 levels show random variations, presumably being affected by ambient conditions, and are therefore not reliable indicators. However, CO concentrations are very consistent over time and therefore **CO appears to be a useful complementary indicator of paper ageing**, which would be useful when furan results are missing or in doubt.

(5) The DGA history for the majority of the failed transformers showed indications of developing faults, generally either the **dielectric or thermal type**. Some transformers have shown early warning indicators for many years before final failure. Some transformers have failed suddenly with no early warning signs of an internal failure.

(6) Transformers that were **overheated** demonstrated significant levels of ethane and methane. The overloading of transformers either from system requirements or overheating of oil (from ineffective cooling systems or design related issues), resulted in a number of transformer failures. The failures were all of a dielectric nature.

CONCLUSIONS

(1) Transformer oil analysis is used extensively by utilities to evaluate the condition of a transformer. Each method has its own merits and needs to be applied appropriately.

(2) The results of the oil analysis that indicate abnormal condition provide a trigger for further offline testing, e.g. Electrical tests.

(3) Furan analysis is a recently introduced condition assessment technique that provides valuable information for assessing the condition of the paper insulation. However, more research is required into the prediction of the end of life for the paper insulation.

(4) The DGA signatures can be used to classify faults in terms of dielectric or thermal faults. The dominant hydrocarbons for a dielectric fault were found to be hydrogen, ethylene and acetylene. The dominant hydrocarbons for a thermal fault are ethylene, methane and ethane.

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