Dissolved Gas Analysis (DGA) role in Improving the Reliability of Wind Farm Transformers in Southern Africa.

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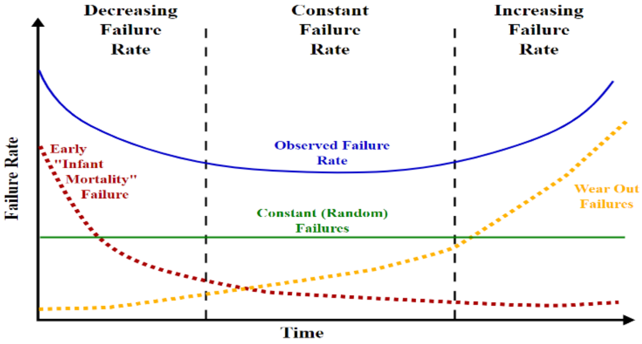
ABSTRACT

Power transformers are expensive and critical equipment in power systems which play a significant role in the transmission and distribution of electricity. Although transformers are generally reliable pieces of equipment, failures do occur, and there are many degradation mechanisms operating in components and sub-systems that will ultimately limit the useful operating life.

Wind Turbine Step-up Transformers that boost turbine outputs from a few hundred volts to medium voltage distribution levels have a high failure rate. This is not unexpected as transformers follow the Bathtub failure curve. This trend affects both liquid filled and dry type transformers.



The 'bathtub curve' hazard function (blue, upper solid line) is a combination of a decreasing hazard of early failure (red dotted line) and an increasing hazard of wear-out failure (yellow dotted line), plus some constant hazard of random failure (green, lower solid line).

Most wind projects utilize pad mount liquid-insulated transformers, and the most common models that have been installed, do have their shortcomings. Many are designed and rated as distribution transformers rather than generator step-up units, which has created a high level of early failures.

This paper will present data indicating that a significant percentage of these Mineral Oil insulated transformers have elevated gas levels. Along with this data, case studies will be discussed on the most likely causes of wind turbine step-up transformer faults detected by Dissolved Gas Analysis (DGA).

Introduction

Assessment of Transformer Active part (magnetic core & windings) can be carried out in three ways i.e.-thermal, dielectric and mechanical assessment. Condition assessment techniques like DGA through testing at laboratory or on-line DGA monitors are used to analyse the symptoms of an incipient fault being developed in transformers based on IEEE/IEC standards and numerous sources of information.
Reference may also be made to ISO 18095 - Condition monitoring and diagnostics of power transformers.

Transformer asset managers are trying to achieve the required levels of safety and reliability from their fleet of transformers at minimum cost. Knowledge of condition is therefore essential for efficient transformer asset management decisions. Without this information only the most basic activities are possible, such as time-based maintenance, replacement before end of life, or repair after failure.

For asset managers, determining the minimum required budgets for maintenance and replacement and determining the most effective and targeted way of spending, is an important task. Often this must be justified to stakeholders and regulators in an increasingly competitive environment.

Good knowledge of plant condition is a crucial step to good asset management. The relative costs of replacement, failure and condition assessment will also need to be assessed to determine the most economic approach.

Insulating Oil testing is typically a critical first step in any power transformer analysis.

The use of dielectric liquid in a transformer provides a valuable way of assessing changes in the internal condition of the transformer. Removing a dielectric liquid sample for dielectric liquid testing and dissolved gas analysis works similarly to a human "blood test" for the transformers. The detection of abnormal patterns of behavior of the dielectric liquid properties offers information about the dielectric liquid itself, as well as transformer components immersed in that dielectric liquid. These dielectric liquid tests are essential for the condition assessment, for the predictive maintenance and for preventing unexpected outages, but they are much more of an investigation than just a test.

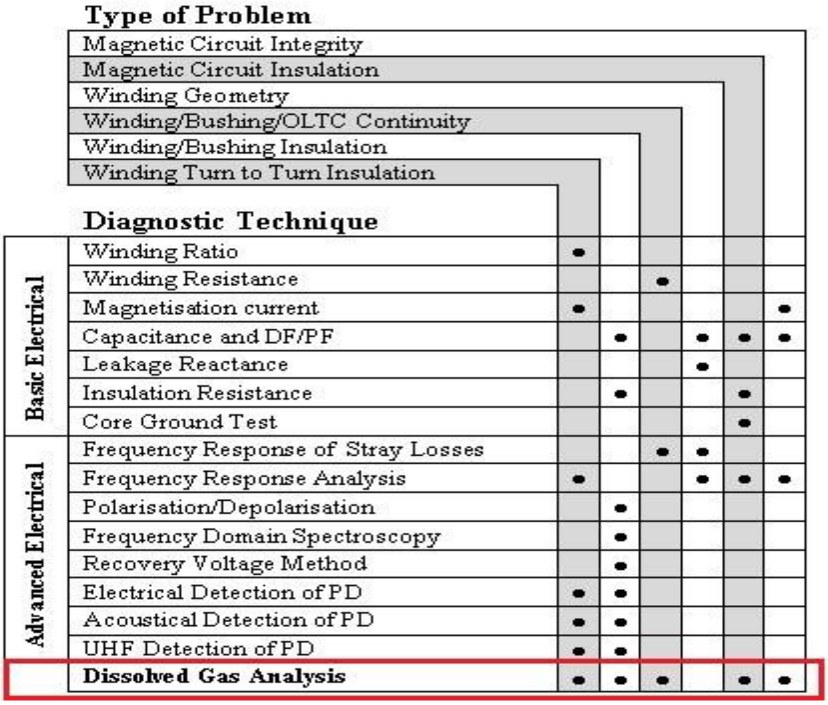
Dissolved Gas Analysis

Dissolved Gas Analysis (DGA) is a powerful diagnostic technique used to analyse dissolved gasses that are generated during the dielectric fluid and solid insulation decomposition process.

Dissolved gas analysis (DGA) has been an industry standard for the detection and determination of faults in transformers for over 30 years. Developed in the late 1960s, DGA has been recognized worldwide as the main tool to prevent catastrophic failures of power transformers.

DGA has become the most informative test for power transformers in our era.
See Figure 1(Cigre WG A2.34- Electrical Tests and DGA Diagnostic Matrix

Figure 1



Type of Problem

	Diagnostic Technique	Winding Turn to Turn Insulation	Winding/Bushing Insulation	Winding/Bushing/OLTC Continuity	Winding Geometry	Magnetic Circuit Insulation	Magnetic Circuit Integrity
Basic Electrical	Winding Ratio	●					
	Winding Resistance			●			
	Magnetisation current	●					●
	Capacitance and DF/PF		●		●	●	●
	Leakage Reactance				●		
	Insulation Resistance		●			●	
	Core Ground Test					●	
Advanced Electrical	Frequency Response of Stray Losses			●	●		
	Frequency Response Analysis	●			●	●	●
	Polarisation/Depolarisation		●				
	Frequency Domain Spectroscopy		●				
	Recovery Voltage Method		●				
	Electrical Detection of PD	●	●				
	Acoustical Detection of PD	●	●				
	UHF Detection of PD	●	●				
	Dissolved Gas Analysis	●	●	●		●	●

Industry experts feel that "Dissolved Gas Analysis (**DGA)** is the most powerful tool in the industry"

The laboratory DGA tests are usually the preferred choice, since its low cost, efficiency and capabilities are in most cases superior to the best available DGA portable and online monitors.

The comparison between laboratories versus online and portable equipment will not be elaborated on, as this subject is addressed in the CIGRE brochure *DGA monitoring systems*, CIGRE Technical Brochure 783, WG D1/A2.47,201.

Importance of Accurate Data for Improving Asset Reliability

Data is the most valuable commodity in today's world, and it is no different in reliability engineering. Inaccuracies can quickly aggregate and escalate from a minor niggle into something that compromises all the efforts that have been previously invested, therefor to obtain a reliable sample plays a critical role.

Transformer Oil Sampling

A program of training the staff with this important aspect had a positive outcome.

This upskilling and certification involved the understanding of the role of data within the company, included what data will be collected, how often, and for what purpose it will be used.

The importance of capturing the correct nameplate information and location was also highlighted as this provides a primary source of information in creating an accurate Asset Register, which is a requirement of ISO 55000.

The first step in any asset management process is to work out what you have and keep the information current.
This may sound easy, but there are challenges, as many sites may be involved, existing asset registers may conflict (different names for the same item).

The author conducting sampling training at a Windfarm.

Some types of equipment may be over-looked therefor site visits are necessary to confirm data.

Data hygiene is an issue that requires constant attention and communication, where there must be clear definitions of roles, consistent with objectives.

The procedure in the use of Dissolved Gas syringes was also covered, as their use improved the accuracy of the DGA data and limited the oil wastage due to the increased sampling frequency.
Note: The test results are only as good as the sample taken (*Garbage in-Garbage out)*

Transformer Oil Testing Laboratories (ISO/IEC/SANAS 17025).

In South Africa there are a limited number of Transformer Oil testing facilities with accreditation to the ISO/IEC 17025 standard, however there is a local proficiency testing scheme, with the specific objective to improve the quality of insulating fluid results.

This paper makes use of DGA data from various sources, and it is encouraging to note that minimal DGA data was rejected as outliers.

There is a lot of confusion about "accredited calibration," why it is required and what it is really about. The correct standard used for calibration and testing laboratory accreditation is ISO/IEC 17025, beyond a quality management system, accreditation is a global standard that recognises the technical competence of a laboratory to perform specified tests.
The ISO/IEC 9001 standard only requires that test equipment used in a facility must be calibrated.

The third edition, published in November 2017, takes into account numerous changes in market conditions that have occurred since 2005.
There is an increased focus on Impartiality, where commercial, financial, or other pressures must not compromise this.
To comply with this clause, only authorised personnel may release opinions and interpretations based on relevant standards.

DGA Interpretation

DGA is an important indicator of dielectric breakdown failure (considered essential). The main gas signatures are:
Hydrogen- Hydrogen is the key gas for partial discharges in oil or gas. Typically, there will be methane
gas present as well.
Carbon Oxides – Dielectric breakdown inside the solid cellulose insulation material will generate carbon monoxide and carbon dioxide.
Sparking Gasses: Partial discharges of the sparking type (IEC 60599 D1 [43]) will create hydrocarbon gasses
Arcing Gasses: Complete breakdown of the insulation material, particularly from winding to winding or winding to ground will result in an electrical arc with high levels of acetylene as well as other hydrocarbon gasses and hydrogen.

Since the 1970's numerous diagnostic schemes have been proposed, all with advantages and disadvantages: Table 1 below

Table 1

➢ Rogers ➢ Halstead ➢ LCIE ➢ Laborelec ➢ GE ➢ Church ➢ Dörnenberg ➢ CIGRE	➢ Potthoff ➢ Shanks ➢ Trilinear Plot ➢ IEC 60599 ➢ Duval Triangle &Pentagon ➢ IEEE C57.104 Key Gas ➢ LCIE Scheme ➢ Potthoff Scheme	➢ 4 Different interpretation methodologies ➢ More than 100 gas level limits ➢ More than 20 ratios ➢ More than 40 faults conditions ➢ More than 10 rates of rise

Duval triangles and Duval pentagon's fault interpretation techniques for mineral oil are now a part of IEC 60599 – 2015 & IEEE c57.104-2019 standards. Using fault categories of Duval triangles and Duval pentagons, the six basic types of faults (PD, D1, D2, T3, T2 T1) are detectable with Duval triangle 1 and pentagon 1, and the five sub-types of faults (T3-H, C, O, S, PD) are detectable with Duval triangles 4, 5 and pentagon 2.

Stray Gassing.

To complicate the interpretation further, there are cases of "stray gassing oils" which can produce gases in transformers at temperatures from 105°C.

Stray gassing of oil has been defined by CIGRE as the formation of gases in oil heated to moderate temperatures (<200 °C). H_2, CH_4 and C_2H_6 may be formed in all equipment at such temperatures or because of oil oxidation, depending on oil chemical structure.
Stray gassing is a non-damage fault and can be indirectly evaluated using the Duval methods.

DGA is a multidisciplinary field and to become an expert on DGA, it is required to study all available DGA related material, literature, and other sources of information.

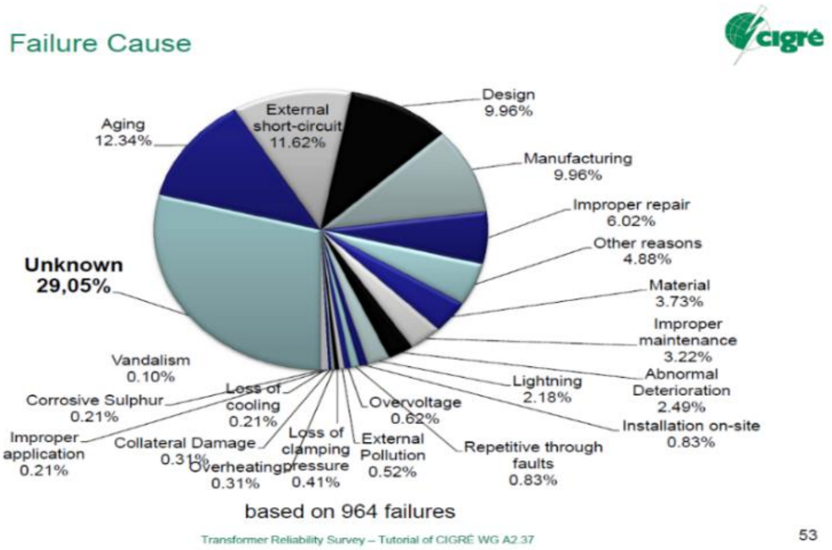
To achieve a >90 % Confidence Normality in DGA interpretation, a combination of the relevant standards and methods is required, where the rates of gas rise are of overriding importance.
It would be good to remember the age-old adage" There is no substitute for experience"

Transformer failures
The risk of transformer failure is two dimensional, namely the severity and frequency.
The consequence of transformer failure is significant due to the following factors

- Damage or injury from fire or explosion
- Environmental damage
- Size and type of load interrupted
- Duration of the possible interruption
- Time to repair or replace the transformer

Generally, the frequency of transformers failures is relatively low but in the changing environment to Renewable Energy, the failure rate is cause for concern due to a number of factors.
There could be many initiators which cause a transformer failure, but those which can potentially lead to catastrophic failure are the following: CIGRE Transformer Reliability Survey WG A2.37(Figure 2).

Figure 2



The causes of Windfarm transformer failures have not been accurately quantified for Southern African countries involved in this just transition to Renewable energy but a study like the Cigre survey would provide some helpful statistics to improve reliability.

Historically the WTG transformer function has been handled by conventional, off-the-shelf distribution transformers. But a relatively large number of recent failures has convinced many that WTG transformer designs must be substantially more durable.

Key characteristics of WTG step-up transformers that wind farm owners and developers should pay attention to include transformer loading, harmonics and non-sinusoidal loads, transformer sizing, voltage variations, and special requirements to withstand faults.

The role of the WTG step-up transformer must be correctly analysed and evaluated. The industry must move from equipment purchasing decisions based on lowest initial cost to equipment that provide a best choice in terms of total cost of ownership, network stability, and less down time and lost revenue from high maintenance issues. Recent transformer technology intended for wind farms should be considered when making purchasing decisions.

The following case studies of Transformer faults detected by DGA will provide some insight to the challenges faced by Windfarm Owners involved with Warranties, Operations and Maintenance.

Example of a unit affected by Improper repair from a Windfarm.

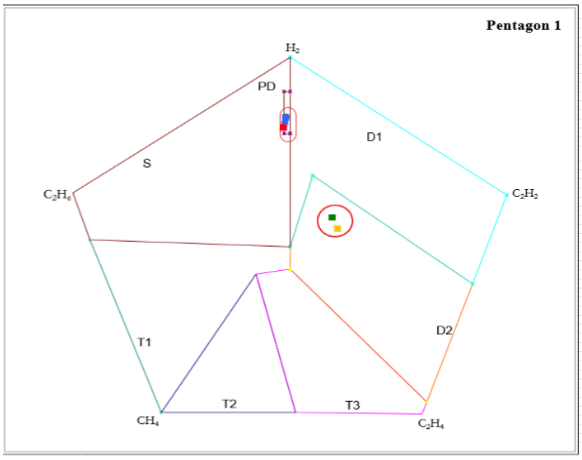
The case of a Pad Mount Transformer WTG 2.7 MVA, 33 kV, without OLTC. Installed in 2016, it had regular DGA sampling performed from the beginning, with high dissolved gas. A partial record of the DGA results is shown in Table 2.
Interpretation of these results using the Duval pentagon's, initially showed a Partial Discharge fault (PD), but following maintenance in July 2017 the fault type changed to a Discharge of High Energy (D2): See Figure 3.

Transformer Assessment Index (TAI) Scoring Matrix (Risk)	**TAI**	**Remedial Action**
Very Poor condition – high likelihood of failure. Component is near end of life. Repair or replacement as soon as possible is recommended. De-rating or restricted operation of the transformer may be appropriate, and operation under extreme conditions may not be appropriate until replacement is possible.	**E**	Resample DGA weekly to monitor Gas Rates of Rise-Plan to remove from service for Inspection/Repairs.

Table 2

Date	H2	CH4	C2H2	C2H4	C2H6
2016/06/07	2942	329	0	6	54
2016/10/12	6857	574	0	6	95
2016/11/02	11908	1232	0	12	276
2016/11/07	12310	1050	0	9	180
2016/11/15	14697	1244	0	13	260
2016/11/23	10710	1329	0	13	276
2017/02/10	13208	1625	0	13	375
2017/06/05	15333	1362	0	8	297
2017/08/14	2463	1047	2256	1569	301
2017/09/01	3169	1063	2237	1566	309

Figure 3



Findings of the Internal Inspection (Root cause Investigation)

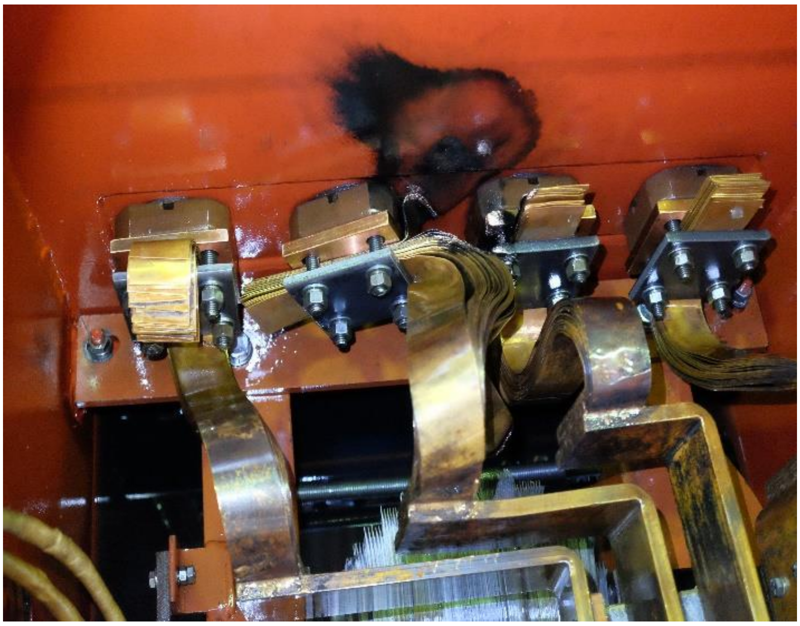
LV short circuit at the LV bushings due to a rotated bushing. It quickly burnt away the touching copper foils which was the cause for the sudden increase in hot metal gasses.

The root cause of the rotated bushing was due to improper maintenance.

The bushing had developed an oil leak and the maintenance contractor attempted to repair this by tightening the Bushing on the outside of the transformer. (Figure 4)

The cause of the initial Partial Discharge Fault (PD) was not established but it is hypothesized that Harmonics played a role, which will be addressed in a subsequent paragraph.

Figure 4



Example of a unit affected by Improper manufacturing from a Windfarm.

The case of a Pad Mount Transformer WTG 2.7 MVA, 33 kV, without OLTC. Installed in 2016, it had regular DGA sampling performed from Factory Acceptance Testing (FAT) to site energisation with all results showing normal operation. However, the sample taken 3 months after Energisation on load showed high dissolved gas, A partial record of the DGA results is shown in Table 3 and the rates of Gas Rise between the samples dated 2018/05/10 to 2018/04/23 is given in Table 5.
DGA values plotted on the Duval Pentagon showed a Thermal Fault (T3)- figure 5.

Table 3

Date	H2	CH4	C2H2	C2H4	C2H6	Type
2017/06/22	0	3	0	1	5	Prior to energising
2017/12/01	0	4	0	1	4	
2018/01/20	0	4	0	2	3	
2018/04/23	1253	9341	1887	27952	4077	
2018/05/10	2300	12264	2163	33951	4949	
2018/10/08	9	4	1	3	3	Prior to Re-energising
2019/06/10	7737	720	2	87	308	

Figure 5

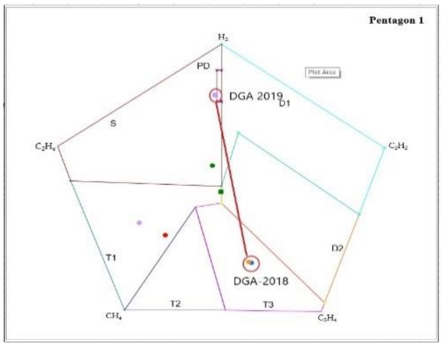


Table 5

	H2	CH4	C2H2	C2H4	C2H6	CO	CO2	TCG
ppm /year	**4109**	**11472**	**1083**	**23544**	**3422**	110	145	43741
Ranges of 90 % typical rates of gas increase (IEC 60599)	35–132	10–120	0−4	32 – 146	5–90	260– 1060	1700-10000	
ppm/day	11,26	31,43	2,97	64,51	9,38	0,30	0,40	**119,84**

Findings of the Internal Inspection (Root cause Investigation).

The In-warranty inspection found a burnt connection on the 33 kV Bus bar link. (Figure 6)
Non-conforming quality control (factory oversight). The first nut was not fastened but the 2nd lock-nut was tightly torqued.
The reason the gas levels increased even though the transformer was de-energised, was the 33kV Links remains energised even when the Isolator is opened to power up the rest of the network. (Daisy chain configured)
A Secondary fault observed on the Core which will contribute to Hysteresis loss and Eddy currents. (Figure 7) and is most probably the cause of the gassing seen in the sample dated 2019/06/10.

Figure 6

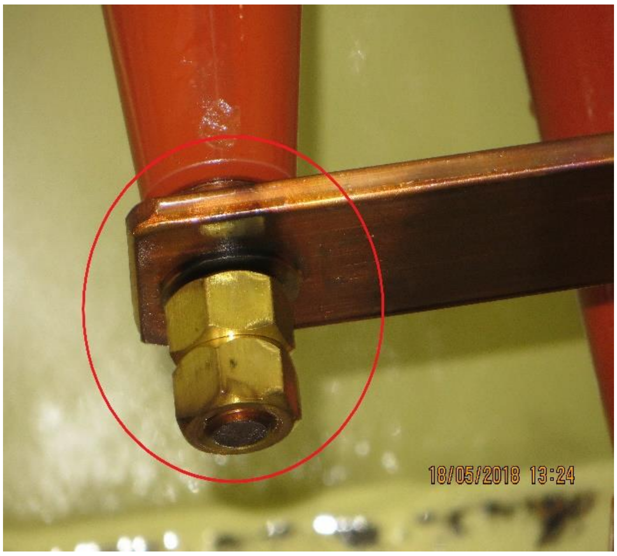


Figure 7

Example of a unit affected by Improper manufacturing from a Windfarm.

The case of a Pad Mount Transformer WTG 2.7 MVA, 33 kV, without OLTC. Manufactured in 2014 according to SANS 780 and installed in 2016. The nameplate information is given in Figure 8.
A full record of the DGA results is shown in Table 6, the rates of Gas Rise exceed the IEC 60599 ranges-See Figure 9.
The Duval Pentagon showed a Thermal Fault(T3) -(Figure 10) as did the Gas Signatures (Figure 11).
Note: The abnormal gassing pattern was evident after Energisation on load, (Warranty issue)
The internal inspection revealed a number of quality issue, figures 12 &13 show some of the faults.

Table 6

Sample Date	H2	CH4	CO	CO2	C2H4	C2H6	C2H2	Sample Type
2018/07/06	35	181	539	8148	729	68	0	
2018/03/06	12	91	312	5393	542	76	0	
2017/10/31	21	147	383	5604	543	71	0	
2017/08/30	33	179	461	6553	647	83	0	
2017/07/18	9	111	233	4645	511	74	0	
2017/06/05	19	144	370	5635	647	74	0	
2017/04/05	18	123	293	4740	569	67	0	
2016/06/13	17	91	901	7494	230	39	1	
2014/02/10	11	3	42	221	1	0	0	Prior energising

Figure 9

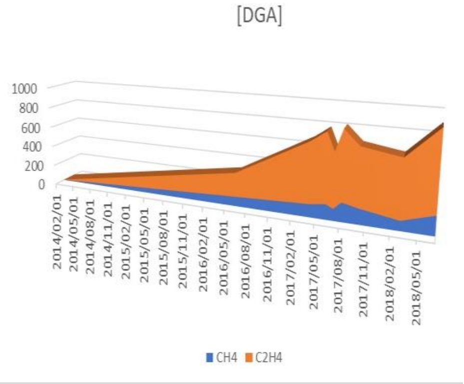


Figure 10

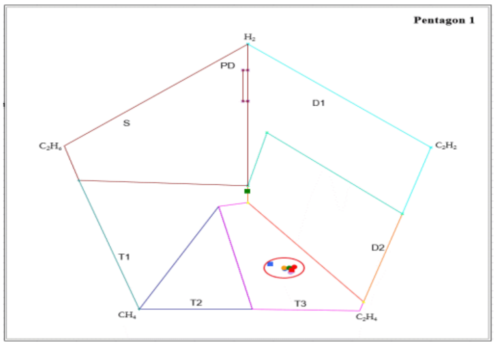
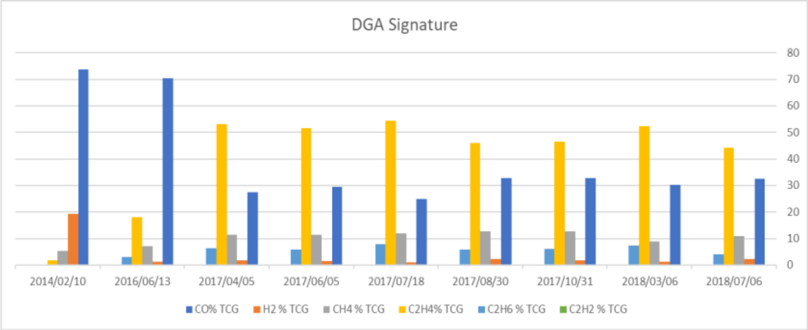


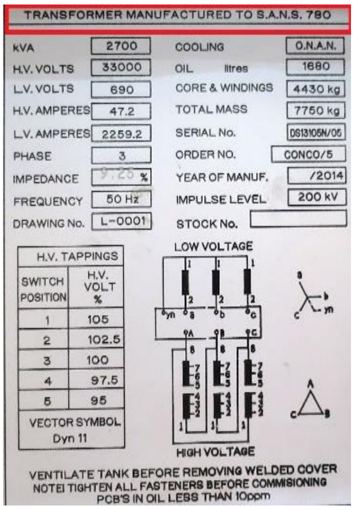
Figure 11



Typical faults in power transformers according to IEC 60599 is given below:

Type	Fault	Examples
T3	Thermal fault *t* > 700° C	Large circulating currents in tank and core Minor currents in tank walls created by a high uncompensated magnetic field Shorting links in core steel laminations

Figure 8: Nameplate



TRANSFORMER MANUFACTURED TO S.A.N.S. 780

kVA	2700	COOLING	O.N.A.N.
H.V. VOLTS	33000	OIL litres	1680
L.V. VOLTS	690	CORE & WINDINGS	4430 kg
H.V. AMPERES	47.2	TOTAL MASS	7750 kg
L.V. AMPERES	2259.2	SERIAL No.	DS13105N/05
PHASE	3	ORDER NO.	CONCO/5
IMPEDANCE	9.25 %	YEAR OF MANUF.	/2014
FREQUENCY	50 Hz	IMPULSE LEVEL	200 kV
DRAWING No.	L-0001	STOCK No.	

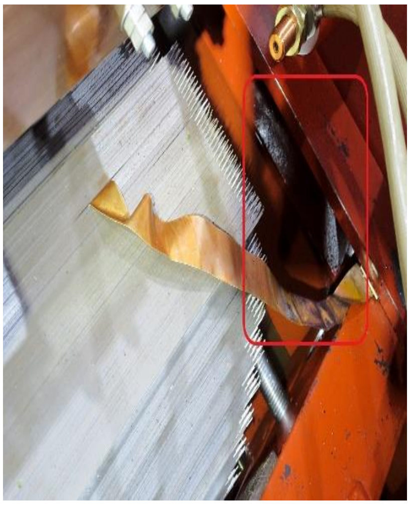
H.V. TAPPINGS

SWITCH POSITION	H.V. VOLT %
1	105
2	102.5
3	100
4	97.5
5	95

VECTOR SYMBOL
Dyn 11

VENTILATE TANK BEFORE REMOVING WELDED COVER
NOTE! TIGHTEN ALL FASTENERS BEFORE COMMISIONING
PCB'S IN OIL LESS THAN 10ppm

Findings of the Internal Inspection: Figures 12&13



Partial Discharge and Harmonics.

In this Case Study of 55 Transformers at a Windfarm, the Dissolved Gas Analysis (DGA), showed a significant number with Abnormal Gas levels when compared to sister Units, as seen in Figure 14. The fault category in most cases was Partial Discharge activity.
According to CIGRE 761 Assessment Index (TAI) Scoring Matrix (Risk), the results are given in Table 7 of Transformer scored as Category D: E: F, while figure 14 shows the Gas Signatures.

Figure 14

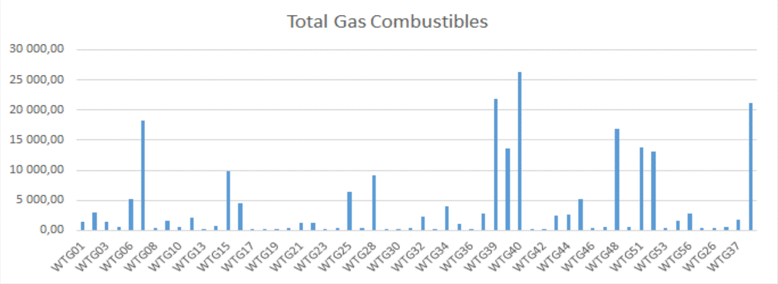
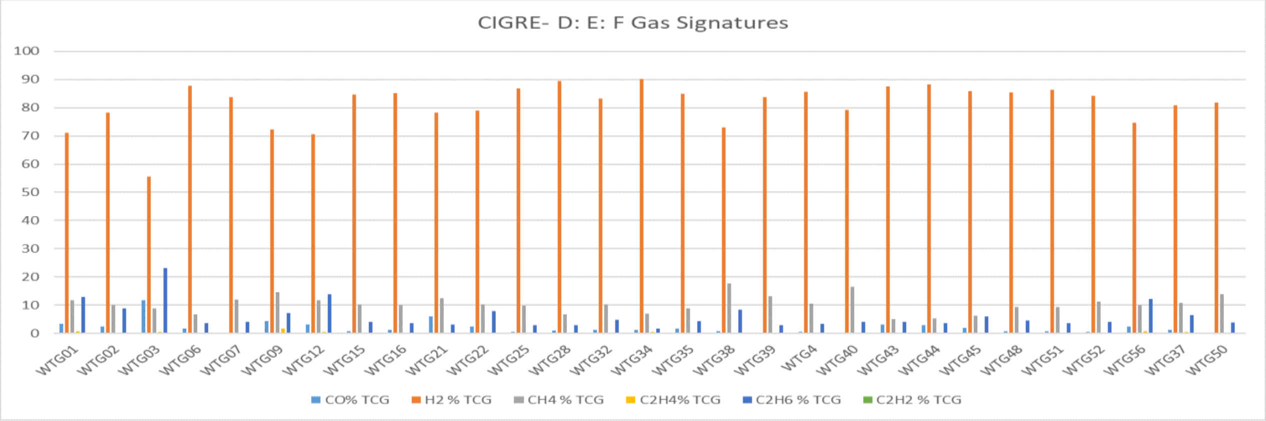


Table 7: CIGRE interpretation.

CIGRE (TAI)	Number of Units	% of Total
>3000 ppm H_2(Cigre F)	14	25,45
>1800 ppm H_2(Cigre E)	21	38,18
>700 ppm H_2 (Cigre D)	29	52,73

F	De-energize as soon as possible. Don't return to service until problem is repaired. Component is at end of life.
E	Very Poor condition – high likelihood of failure. Component is near end of life. Repair or replacement as soon as possible is recommended. De-rating or restricted operation of the transformer may be appropriate, and operation under extreme conditions may not be appropriate until replacement is possible.
D	Poor Condition. Repair or replacement should be considered within the short term. Reliable operation may be impaired or compromised. Performance or component may be causing deleterious effects. Consider review of rating and operating condition.

Figure 14



The main cause of the PD was identified as sharp edges on the foil windings as well as bad workmanship in the factory exacerbating the PD due to stop-blocks damaging the paper. The process followed to properly cure the diamond dotted paper had not been followed correctly resulting in the paper not curing to the foil properly or even at all. Harmonics was also a role player.

Harmonics

The energy generated by the wind turbine is disruptive in several ways. Wind turbines often cut in and out several times a day, except in ideal wind conditions. This erratic load level can create multiple in-rush currents and, more importantly, thermal cycling beyond the design of the transformer. The AC current is often 'polluted' with harmonics, in many applications, typically not producing the clean sine wave that equipment, such as transformers, expect to see.
Unfortunately, the subject of harmonics is complex and extensive but there is compelling evidence of a link to the gassing issues in windfarm transformers. It's certainly worthy of additional investigation in respect to the Partial Discharge activity detected by DGA.

Partial Discharge and Safety concerns.

Partial discharge activity typically occurs within insulation voids, on ungrounded metal objects lying in an electric field, or as corona due to the intense electric stress on the insulation surrounding sharp edged electrodes.

The long-term effect of PD is destructive for insulation systems, by degrading their insulation qualities. A significant increase of the PD level or the rate of the PD can provide an early indication for evolving defects. The PD pulses generate electro-magnetic waves, acoustic signals, chemical reactions, local heating, and optical signals. Different techniques can be used to detect these phenomena and thus infer the presence of PD

Safety Concerns of High Levels of Hydrogen and Hydrocarbons in Active Transformers

Due to the volatility and buoyancy of hydrogen and the Hydrocarbons (CH_4: C_2H_4: C_2H_6:C_2H_2), it is generally recognized that concentrations of 4-74% are flammable and at 18-59% the mixture is explosive. It could be expected that the concentration of H_2 and the Hydrocarbons may be even higher in the transformer's gas space. This means that a spark in the gas space must be avoided at all costs.

Safety concerns of Gas Bubble formation

Gas bubbles lower the effective dielectric constant of the oil which in turn increases the electric stress in the oil and in particular across the Gas bubbles. The high stress causes voltage breakdown across the Gas bubbles, these Gas bubbles elongate in the direction of the electric field resulting in flash-over-voltage stress.

Standards

Clearly there is much work to be done before all the issues associated with wind farm transformers can be understood. The industry needs to move from outdated standards to accepted International best practice, like the new Dual Logo Standard IEC/IEEE 60076-16, that might help guide wind farm owners to more trouble free and reliable systems. To support this effort, the cooperation and input of all interested parties throughout this industry is needed.

Conclusions

This head-long rush to install more and more wind turbines has outstripped the usual developmental learning curve where new technologies mature by a process of trial and error, but the use of properly applied Dissolved Gas analysis has already made a positive contribution in improving reliability.
The increased efficiencies in transformer reliability will contribute to enhanced worker safety, while ensuring the overall profitability of wind projects improves and reduces the effective cost of wind energy production.

Providing a quality service.

Michael Venter *Business Unit Manager Consolidated Power Projects had this to say.*
“I would like to thank you for the valued input we receive from you and your team.
We are “making history” as we are slowly but surely resolving the transformer gassing issues experienced in the industry at the moment in South Africa.
Please thank your team on our behalf for their level of commitment and service to resolving this issue.
We are of the belief that the latest design, will finally resolve this issue. (Perdekraal and Kangnas Wind Farms, will be installed with the latest design units, 109 in total)
The role you and your team played in this process cannot be ignored and I would like to thank you for that.

Further considerations

I have always been intrigued by the lack of knowledge sharing and collaboration on best practices of design specifications, condition assessment, maintenance and maximizing lifecycles of power transformers, is an issue that needs attention.
We have accumulated substantial behavioural data on older and newer designs, but we need to do a better job in sharing transformer behavioural analytics amongst ourselves for more reliable performance indicators.
This would let us to identify genetic or design-related problems, predict failure mechanisms and be proactive.

Knowledge and data sharing among end-users can also help to compensate for unfamiliarity with a specific type of critical component, technology, or supplier.

Sharing the post-mortem and failure pattern data would provide the ability to anticipate a failure mechanism without any prior experience.
The current Non-Disclosure Agreements (NDA) circumvent the ideal of knowledge sharing and should be addressed by the industry.

Acknowledgments

The author of the paper would like to express gratitude to all contributions.

References

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