OPTIMISATION OF ONLINE CONDITION MONITORING TO PREDICT POWER TRANSFORMER FAILURES IN DISTRIBUTION NETWORKS

by

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Declaration

I, Thabang Abel Motau, hereby declare that this research project which has been submitted to the Central University of Technology, Free State for the degree of MASTER OF ENGINEERING (ELECTRICAL ENGINEERING), is my own independent work; complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State; and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

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Date: 2019-04-24

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Abstract

The stability of any distribution network is very much dependant on the performance of the power transformers. These transformers need to be monitored to ensure that any unwanted conditions, including high risk defects, are detected. The previous and current transformer failures in the Northern Cape Operating Unit show that the health status in the Plant Health Indicator of the transformers was on category A. Category A status means the transformers were healthy. The root causes of failure were that only some of the Dissolved Gas Analysis parameters were monitored. The transformers were shown to be healthy by the Plant Health Indicator at the time of the failure. Parameters such as cooling, bushings, tap changers, operating temperatures, ageing and loss of life were not monitored. The majority of transformer failures recorded were affected by the parameters mentioned above, of which some are not monitored in the Plant Health Indicator.

This research study discusses the application of integrated online condition monitoring for power transformers as one of the techniques to assess the condition of the power transformer during operation. The integrated online condition monitoring allows for transformer condition assessment without having to switch off the transformer, thereby minimising power supply interruptions. The integrated online condition monitoring system is unique technology that monitors the condition of various parameters of the power transformer such as the cooling fans, on-load tap changer, bushings, transformer operating temperatures, dissolved gas analysis, transformer ageing and loss of life. The research design is quantitative with data analysis retrieved directly from the online condition monitoring server. The results from the bushings, cooling fans, tap changer and temperatures form part of the analysis.

Data analysis lead to a discussion of these parameters, which highlights the problems currently experienced with transformer failures in the Northern Cape Operating Unit.

The research study revealed that, although Eskom is having the best maintenance practices in power transformers, there is a need to improve and save costs, as the current maintenance strategies of power transformers are expensive. The results of the study should be regarded as exploratory, and provide directions to researchers for further, more in-depth studies in this field. The cost analysis was performed over a period of ten years, as compared to the current costs of maintenance/monitoring and asset replacement strategies of power transformers. The total saving per year was a great benefit for tasks such as inspections/maintenance/monitoring and asset replacement. This was validated by the results from the proposed transformer online monitoring technology that can predict the defects which may result in catastrophic transformer failures.

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Nomenclature

C_2H_2	Acetylene [ppm]
C_2H_4	Ethylene [ppm]
C_2H_6	Ethane [ppm]
CH_4	Methane [ppm]
CO_2	Carbon Dioxide [ppm]
C_X and R_X	The unknown capacitor to be measured
C_1	Standard capacitor of known capacitance of high precision and stability
d^1	Date for y^1
d^2	Date for y^2
D1	Low energy discharge
D2	High energy discharge
DT	Mixture of electrical and thermal faults
H_2	Hydrogen [ppm]
I	Maximum continuous current (pu)
m	Mass of oil [kg]
ml	Millilitre
MVArated	Rated MVA on primary tap
PD	Partial discharge
R_1	Standard resistor of known resistance of high precision and stability
R_2 and C_2	Variable components used for balancing the bridge
T1	Thermal faults $T < 300$ °C
T2	Thermal faults 300 °C $< T < 700$ °C
T3	Thermal faults $T > 700$ °C

V	Voltage on primary side (pu)
y^1	Reference analysis value
y^2	Last analysis value
ρ	Density of oil [kg.m-3]

Abbreviations

AC	Alternating Current
AM	Ante Meridiem
CBM	Condition Based Maintenance
CSUS	California State University Sacramento
DGA	Dissolved Gas Analysis
DNP3	Distributed Network Protocol
ETRA	Electric Technology Research Association
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
KDS	Kimberley Distribution Substation
KPI's	Key Performance Indicators
KV	Kilo Volt
LAN	Local Area Network
MMA	Month Moving Average
MVA	Mega Volt Amp
NCOU	Northern Cape Operating Unit
NEMA	National Environmental Management Act
NRS	National Regulatory Services
OFAF	Oil Forced Air Forced
OFAN	Oil Forced Air Natural
OFWF	Oil Forced Water Forced
OIP	Oil Impregnated Paper

OLTC	On-load Tap Changer
ONAF	Oil Natural Air Forced
ONAN	Oil Natural Air Natural
OTI	Oil Temperature Indicator
OU’s	Operating Units
PD	Partial Discharge
PHI	Plant Health Indicator
PM	Post Meridiem
PPM	Parts Per Million
RIP	Resin Impregnated Paper
SCADA	Supervisory Control and Data Acquisition
SMS	Short Message System
TBM	Time-based Maintenance
TCP	Transmission Control Protocol
TDCG	Total Dissolved Combustible Gases
VPN	Virtual Private Network
WAN	Wide Area Network
WTI	Winding Temperature Indicator

CHAPTER 1: INTRODUCTION

1.1 Background

Power transformers are some of the most critical and expensive assets in the distribution business. They need to be efficiently operated and maintained throughout their life cycle to maximise design life and prevent failures. The Northern Cape Operating Unit (NCOU) uses the transformer Plant Health Indicator (PHI) tool to monitor the health condition of the installed transformer fleet. This tool uses only Dissolved Gas Analysis (DGA) to predict the health and ranking of power transformers.

The previous and current transformers failures in NCOU show that the health status in PHI of the transformers was rated as category A. This category A status means that the transformers were healthy. Thus, only certain DGA parameters were monitored, which caused the problems. Transformers were indicated healthy by PHI at the time of the failure. Parameters such as cooling, bushings, tap changers, operating temperatures, ageing and loss of life were not monitored. The majority of transformer failures recorded were affected by the parameters mentioned above – some of which are not monitored in PHI.

The certain parameters during time-based maintenance (TBM) cycles such as annually, three yearly and six yearly are not covered. During annual, three-yearly and six-yearly cycles, TBM only covers oil sampling, tap changer, routine electrical tests in the active part (windings), and protection device and temperature measurement device functional tests.

There are many reasons why power transformers must function reliably continuously, such as high customer demands, processes and increasing load requirements. For these reasons, monitoring solutions are required that provide constant information about the current status of equipment, so that proactive steps can be taken to ensure high availability and a longer service life. In many countries today, over 70 per cent of transformers have been in use for over 25 years [1].

The actual average service time often exceeds the estimated service life. Backup transformers are already being used for routine operations, and in many cases, spare parts are no longer available. Moreover, transformers are not only being used at their nominal capacity, but even to the maximum load capacity [2].

Their reliability and performance remain of great importance to the utilities. Regardless of their failure rate, transformers play a key role in distribution networks. The TBM philosophy and PHI are currently used in NCOU power transformers' (1MVA to 80MVA) maintenance. These philosophies were investigated and found to be ineffective in reducing power transformer failure rates.

1.1.1 Condition-based maintenance strategy

The maintenance strategy, other than the simplest time-based strategy, will depend on feedback on the condition of the transformer. Condition-based maintenance (CBM) is an important strategy in asset management that would allow a transformer to operate according to its actual rated efficiency. This maintenance is carried out depending on equipment condition to reduce the likelihood of an item of equipment failing in service. The term "conditional preventive maintenance" is also used. CBM is based on assessing the actual physical condition of the asset, and takes into account its usage, occurrence of events, possible wear of moving or current switching parts, and the performance of similar equipment [3].

In order to use this maintenance philosophy, it is necessary to assess the asset condition by methods such as online condition monitoring. CBM applies in cases where technical conditions can be measured and assessed against criteria for invoking action. Incorporating CBM in a maintenance strategy seeks to reduce costs by performing maintenance only when a change in equipment condition warrants taking action. CBM however requires a more complicated planning process. CBM is often used within a time-based outage plan to defer maintenance to the next available outage. Better transformer management could be achieved with online monitoring, routine diagnostics and CBM [3].

1.1.2 Condition monitoring in power transformers

Power transformers are the most expensive single elements in distribution networks. Therefore, it is an aim of the utilities to decrease the transformer life cycle costs and to increase their usable service life. One way of accomplishing this is through the extension of the well-known classical methods of transformer supervision by an advanced monitoring concept. To meet the expectations, a transformer monitoring system has to fulfil numerous requirements. The maintenance strategy, other than the simplest time-based strategy, will depend on feedback of the condition of the transformer. To be useful, however, a condition monitoring task must be technically and economically justifiable. The technical justification depends on whether a condition can be detected and corrected before a loss of performance occurs [3].

Figure 1.1 below shows a theoretical condition in terms of degradation as a function of time for a transformer.

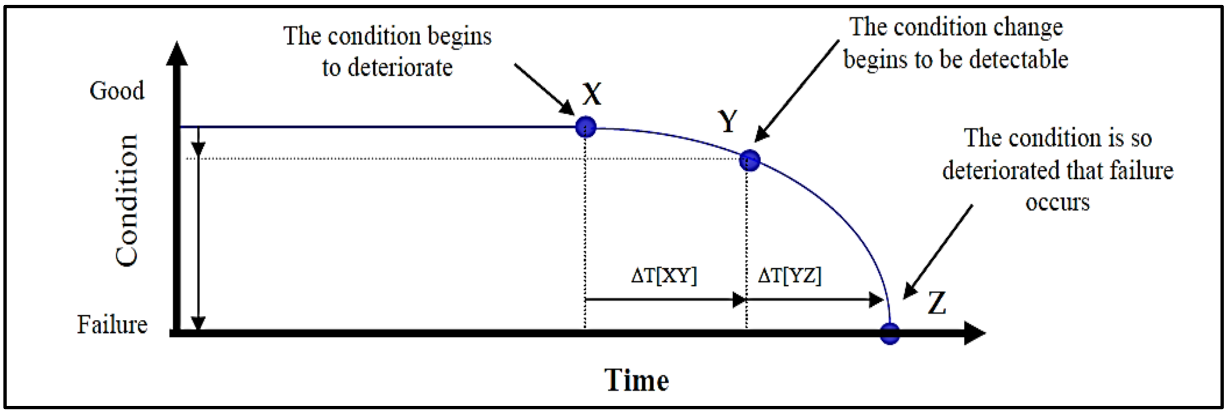


Figure 1.1: Theoretical transformer condition degradation [3]

To be technically feasible, a condition monitoring task should have the ability to:

— detect a given condition change that is relatively small compared to the condition change where the failure occurs;

— have a measurement or inspection interval that is smaller than ΔT [XY] +ΔT [YZ] to allow detection before failure occurs;

— have a period of time ΔT [YZ] that is long enough to be able to take the preventive action (transformer outage).

The early detection of underlying deterioration will reduce the risk of failure if timely action is taken. Condition monitoring based on measurements can only be as good as the integrity of the data. The application of a condition monitoring programme to a large group of identical transformers sometimes identifies a problem in one unit that then allows the timely application of corrective actions to all members of the group [3].

The main objective of investigating the currently used PHI tool and TBM philosophy was to determine the effectiveness and financial viability of online condition monitoring techniques for failure prediction on power transformers. The specific objective was to establish whether, based on historical evidence, a failure could have been predicted prior to a power transformer failure based on the practice of an online condition monitoring technique. NCOU operates a variety of high voltage equipment with the main goal of supplying electricity continuously by means of an interconnected grid.

Transformers are the most expensive pieces of equipment in the substation, and require a specialised skill to ensure optimal utilisation within their lifespan. All degradation and ageing processes of the oil-paper insulation produce gases. The most important transformer fault gases are Hydrogen (H_2), Carbon Dioxide (CO_2), Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4) and Ethane (C_2H_6). These gases are dissolved in the oil, and if a certain level is exceeded, gas bubbles arise. These gas bubbles can be transported into regions with high electrical stresses and will lead to Partial Discharge (PD) activities. At present, the gas-in-oil analysis (DGA) is the most important and most effective method for transformer diagnostics [4].

NCOU spends a lot of funds in replacing failed substation power transformers, and at times even before the power transformer reaches its end of life. As a result, the unnecessary interruptions due to power transformer failures affect the key performance indicators (KPIs) significantly. This study will look at the opportunities and benefits of introducing online condition monitoring techniques on substation power transformers in order to reduce the high failure rate of power transformers within the Northern Cape Operating Unit Network.

The research will introduce the integrated online condition monitoring for power transformers as one of the techniques to assess the condition of the power transformer during operation. The integrated online condition monitoring allows for transformer condition assessment without having to switch off the transformer out of service, thereby minimising power supply interruptions. The integrated online condition monitoring system is a unique technology that monitors the condition of various parameters of the power transformer such as cooling fans, on-load tap changer, bushings, transformer operating temperatures, dissolved gas analysis, transformer ageing and loss of life.

The data and remotely collected information from this system is used to determine the cooling state, ageing rate, transformer lifetime estimation and the prediction of transformer failure before it could happen. The collected information is also used to support maintenance planning by assisting to identify the relevant maintenance activities/interventions (CBM) required on the power transformers [4].

Limitations of study:

For the purpose of this study the online condition monitoring methods will monitor the following conditions:

- cooling;
- on-load tap changer;
- bushings;
- dissolved gas analysis;

- transformer operating temperatures; and
- transformer ageing and loss of life.

The online condition monitoring technique cannot be used in old transformers (30 years and older) as a result of the technology design limitations, since the fitting of the online monitoring sensors is not possible. Hence, monitoring of old transformers will be excluded in the study.

Only newer transformers (30 years and younger) fitted with the latest technology will be utilised for purposes of this study. The other limitation is Eskom's restricting firewall cybersecurity policy to create Virtual Private Networks (VPN) in order to retrieve data via a web interface browser.

The additional limitation is that SITRAM Transformer Diagnostic and Condition Monitoring (TDCM) is fitted with Modbus Ethernet communication protocol as per European standards. Hence, a conversion of the format of data from Modbus to DNP3/IEC101 is needed for Supervisory Control and Data Acquisition (SCADA). A further limitation will be the approval of the outages by management to fit in the sensors in the transformers. Furthermore, benchmarks are not conducive to the South African context.

Additionally, the online condition monitoring start-up costs (skilled Engineers, hardware and software, etc.) are very high. Therefore, there might be a lack of funds to purchase and install the online condition monitoring equipment in all transformers within the Northern Cape Operating Unit.

1.2 Problem statement

1.2.1 The failure rate for substation power transformers in Northern Cape Operating Unit

The Northern Cape Operating Unit possesses 5% of the Eskom Distribution Division's power transformers (205 out of 4 168). NCOU also contributes to 1.96% of all the failures in Eskom's distribution over a 12-month moving average [5].

In order to assist NCOU to address their failure rate, and to understand the challenges and philosophies in NCOU, a research study was conducted, consisting of failure investigations and performed statistical analysis of NCOU's transformer data. Ultimately, the purpose of this research was to identify the technology to assist in the reduction of the number of transformer failures in NCOU. Transformer failures impact greatly on network performance in terms of reliability and sustainability, customer satisfaction and cost, and should be avoided at all costs.

1.2.2 Power transformer failure poses a danger to human life

Power transformers are employed in the network to transform power from one voltage level to another in order to reduce the transmission losses (step-up), and to make the power available to the customers at the agreed voltage level, adequate for the end-user equipment (step-down).

When the transformers fail and catch fire, the most likely causes are windings, tap changers, and bushings, listed in the ascending order. For a fire to ignite and be sustained there are three elements that are required and in appropriate proportions. They are heat, fuel and oxygen. In the case of transformers or any oil-filled high voltage equipment, the heat comes from the arc when there is a dielectric breakdown. The oil and/or other combustible items act as fuel, and the atmospheric air provides oxygen [6].

If any of the elements is removed or is not available in an adequate proportion, the fire will not be started and/or sustained. It is for this reasons that failures of non-terminal items such as windings and cores are unlikely to cause fire. When an electric failure takes place, hot gas plasma is created around the failure point. The volume of such gas plasma will depend on the energy involved in the failure and the time it takes to remove the electrical energy source from the faulty equipment [6].

The number of transformer failures that resulted in fires is a great worry within NCOU. This is a safety issue, and the damage is often significant, resulting in the replacement of other bay equipment which increases the restoration time and is extremely costly. The explosions and fires resulting from transformer failures are posing a serious danger to human life. These explosions and fires can result in fatalities, especially when there are humans present in the substation during the time of transformer failure.

The pieces of debris (i.e. porcelain, bushing pins, etc.) as a result of explosions can be found approximately 60 metres away from the failed transformer. Thus, if there are humans in the vicinity during explosions there is a high possibility that they can be hit by these flying objects.

1.2.3 Outages, primary equipment damage and collateral damages are very costly

The financial burden of transformer failures and the immediate action to restore supply are well known, as well as the associated impact on the KPIs, the organisation's image and customer satisfaction.

In addition to these issues, the failure of a transformer has far reaching consequences for the business that may include:

- The high failure rate directly affecting the number of spares to be kept, as the required stock level is a function of failure rate. Additional spare transformers equates to additional transport, rigging and eventually maintenance at the stores.
- The high failure rate in NCOU also puts other operating units (OUs) at risk, as their spares are depleted in assisting NCOU during failures.
- The costs of transporting spares from other OUs to NCOU are also higher due to the cost of transport over the longer distances. This also affects restoration times.

Due to their high cost (a transformer forms a major portion of the capital investment required for a substation), utilities place great emphasis on the life cycle management and correct operation of transformers in service. The expected lifespan of a transformer employed in the distribution network is 35 years when operated at rated condition, but this lifespan can be exceeded or reduced depending on various factors in the design, manufacturing and operation of the transformer. In the current difficult economic climate, it is imperative that the number of transformer failures is kept to a minimum [7].

1.3 Objectives of the study

The aim of this study is to look at the opportunities and benefits of introducing online condition monitoring techniques on substation power transformers in order to reduce the high failure rate of power transformers within the Northern Cape Operating Unit.

The objectives of this study are as follows:

- To introduce online condition monitoring techniques on substation power transformers in order to reduce the high failure rate of power transformers.
- To monitor the cooling, on-load tap changers, transformer operating temperatures, bushings, dissolved gas analysis and transformer ageing and loss of life.
- To use the Dissolved Gas Analysis (DGA) method as fault diagnostic for the detection of incipient or potential faults, and thus for assessment of transformer condition.
- To perform a cost analysis study of online condition monitoring systems, in comparison with time-based to condition-based maintenance in power transformer maintenance.

1.4 Research methodology

To achieve the above-mentioned objectives, the methodology is as follows:

<u>Literature review</u>: An online condition monitoring technique on substation power transformers in Eskom Distribution - particularly in the Northern Cape Operating Unit - will be introduced. The online condition monitoring technique will assist in preventing the probability and consequences of power transformer failures within distribution networks.

<u>Selection of distribution substation</u>: A Kimberley distribution substation in the Northern Cape Operating Unit was selected as the study site. The site is situated at 28°44'35.0144" S and 24°48'53.6754" E.

The continuity of supply is a requirement for the selected distribution substation, and the site was selected based on the number of power transformer failures that have occurred at the site. The proposed online condition monitoring technique will assist in preventing the probability and consequences of power transformer failures. The online condition monitoring data of power transformer parameters of the selected site will be collected. SITRAM Transformer Diagnostic and Condition Monitoring, Kelman Transfix 1.6E transformer gas analysers and Bushing monitoring devices will be used to collect data on site.

Cost analysis: Cost analysis of the proposed transformer online condition monitoring will be performed through the use of the EXCEL software. This software was developed by a Microsoft Office Windows professional. It was used to show the savings per annum in maintenance/monitoring and inspection costs at the study site.

System modelling: Different methods for oil analysis will be used to determine the condition of the active part on power transformers, and to describe the performance of the proposed system. SITRAM Transformer Diagnostic and Condition Monitoring, Kelman Transfix 1.6E transformer gas analysers and Bushing monitoring devices will be used to collect data on site, and data will be analysed and optimised to predict the power transformer failures on distribution networks.

1.5 Hypothesis

1. The online condition monitoring on substation power transformers can reduce the high failure rate of power transformers in Eskom Distribution, compared to the TBM philosophy and transformer PHI tool that is currently used in NCOU power transformers at the study site.

2. The results of the investigation carried out on the equipment that failed during operation indicated that NCOU contributes to 1.96% of all the failures in Eskom's distribution 12 month moving average. It can be concluded that 46% of power transformers have their failures attributed to defective windings. The other 9% have their failures attributed to tap changers; 36% to bushings, and 1% to "end of life". It will be cheaper to monitor the power transformers than to wait for them to fail.

1.6 Limitations of the study

The study has been conducted with the following limitations as stated earlier:

- The online condition monitoring technique cannot be used in old transformers (30 years and older) because of the technology design limitations, since the fitting of the online monitoring sensors is not possible.
- International benchmarks are not conducive to the South African environment. Additionally, the online condition monitoring start-up costs (skilled engineers, hardware and software etc.) are very high.
- There might be a lack of funds to purchase and install the online condition monitoring equipment in all transformers within the Northern Cape Operating Unit.
- The restriction of Eskom's firewalls cybersecurity policy to create a Virtual Private Network (VPN) in order to retrieve data via a web interface browser.
- The SITRAM Transformer Diagnostic and Condition Monitoring is fitted with Modbus Ethernet communication protocol as per European standards. Hence, a conversion of the data format from Modbus to DNP3/IEC101 is needed for Supervisory Control and Data Acquisition (SCADA).

- Another limitation might be the approval of the outages by management to fit the sensors in the transformers, as the affected substation is supplying important customers.

1.7 Contribution to knowledge

- The author presented a global review of online condition monitoring based on recent development studies, suggestions, relevant technologies and applications in preventing the probability and consequences of power transformer failures. This will enable the researchers to identify more research gaps in the adoption of technology in order to prevent the power transformer failures.
- The high number of power transformer failures as a result of the TBM philosophy and transformer PHI tool that is currently used in NCOU, as compared to transformer online condition monitoring at the specified study site, will be reduced.
- The online condition monitoring announces the change of transformer condition in advance of failure. The technology forms the basis for Condition Based Maintenance and can effectively reduce the risk of unexpected catastrophic failures.
- The development of an online condition monitoring model to assist with performance evaluation of power transformer parameters (fans, on-load tap changers, bushings, transformer operating temperatures and dissolved gas analysis) during the planning stage is presented.

1.8 Outline of the dissertation

Chapter 1 is an introduction to the dissertation, which presents the background, problem statement, objectives, methodology, hypothesis, limitations of the study, as well as the research outputs.

Chapter 2 provides a comprehensive overview of the online condition monitoring technique usage and potential within Eskom Distribution Networks. The primary focus is based on the opportunities and benefits of introducing online condition monitoring techniques on substation power transformers in order to reduce the high failure rate of power transformers within distribution networks. A review of online condition monitoring techniques, developments, suggestions, evaluations, improvements as well as the usage of international models for oil analysis will also be included.

Chapter 3 provides a cost analysis of the proposed online condition monitoring to be performed through the use of EXCEL software. It has been used to show the savings per annum in maintenance/monitoring and inspection costs at the study site. This saving per annum benefit is compared to the TBM philosophy and transformer PHI tool that are currently used in NCOU power transformers at the study site.

Chapter 4 covers the proposed online condition monitoring data of power transformer parameters of the selected site that will be collected. SITRAM Transformer Diagnostic and Condition Monitoring, Kelman Transfix 1.6E transformer gas analysers and Bushing monitoring devices will be used to collect data on site.

Chapter 5 discusses the analysis of the collected data of the developed model. International models for oil analysis will be used to determine the faults on power transformers, and also to describe the performance of the proposed system. SITRAM Transformer Diagnostic and Condition Monitoring, Kelman Transfix 1.6E transformer gas analysers and Bushing monitoring devices will be used to collect data on site, and data will be analysed and optimised to predict the power transformer failures on distribution networks. The advantage/benefit of using this proposed technology will then be compared with the TBM philosophy and transformer PHI tool that are currently used in NCOU power transformers at the study site within Eskom Distribution.

Chapter 6 presents the conclusions and suggests future areas of research to be carried out in order to promote the online condition monitoring technology.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a brief review of the current status and potential of online condition monitoring of power transformers in South Africa. It reviews the global status of online condition monitoring of power transformers in the substation environment applications. The online condition monitoring systems deliver a valuable contribution for early detection of malfunctions, for general gathering of condition information and diagnosis in power transformers.

2.2 Prominence of Online Condition Monitoring of power transformers and implementation of the concept in South Africa

South Africa has a considerable number of power transformers installed in the network. Over the past few years many transformer monitoring techniques and systems have been developed, offering a variety of advantages for the transformer operator and asset manager. These advantages range from the ability to know the overload capability of the transformer to detailed monitoring of faults in the active part and accessories such as bushings and tap changers. The cost and complexity of monitoring systems vary widely, and the application of all the available techniques to all transformers from new is not financially justified. Instead a mix-and-match approach is more likely to be appropriate, with the customer able to choose which type of monitoring is most appropriate, depending on the importance and health of the transformer [1].

However, no major development has been made in South Africa to introduce the online condition monitoring of power transformers in the networks by electricity utility companies for almost 20 years. Expensive costs and skills inhibit interest in implementing the online condition monitoring of power transformer technology in South Africa. Only little attention has been paid to the utilisation of online condition monitoring of power transformer technology in critical substations.

Currently, around 4 128 power transformers (1MVA up to 160MVA) are installed within Eskom Distribution networks across South Africa, as shown in Table 2.1. This excludes pole mounted transformers (500kVA and below). It emphasises the requirement for online condition monitoring of power transformer technology in South Africa because of the high number of installed power transformers within Eskom Distribution, as well as the high number of transformer failures [5].

Currently there is no power transformers fitted with the online condition monitoring technology in Eskom Distribution.

Table 2.1: Total number of installed power transformers in Eskom Distribution [5]

Operating units power transformer installation status Eskom Distribution	
Operating unit	Installed number of transformers
Eastern Cape	237
Free State	468
Gauteng	960
KwaZulu Natal	395
Limpopo	409

Mpumalanga	582
Northern Cape	205
North West	525
Western Cape	347
Eskom Distribution Total	**4 128**

Power transformers are one of the most critical and expensive assets in the distribution business. They need to be efficiently operated and maintained throughout their life cycle to maximise design life and prevent failures. The Northern Cape Operating Unit (NCOU) uses the transformer Plant Health Indicator (PHI) tool to monitor the health condition of the installed transformer fleet. This tool uses only Dissolved Gas Analysis (DGA) to predict the health and ranking of power transformers. The previous and current transformer failures in NCOU show that the health status in PHI of the transformers was on category A.

The category A status means the transformers were healthy. This outcome is based on the fact that only certain DGA parameters were monitored, and the transformers were indicated healthy by PHI at the time of the failure. Parameters such as cooling, bushings, tap changers, operating temperatures, ageing and loss of life were not monitored. The majority of transformer failures recorded was affected by the parameters mentioned above, some of which were not monitored in PHI.

The results of the investigation carried out on the equipment that failed during operation are shown in Figure 2.1 below. It can be seen that 46% of the power transformers have their failure attributed to defective windings. As far as the rest are concerned, 9% have their failure attributed to tap changers, 36% to bushings, and 1% to end of life.

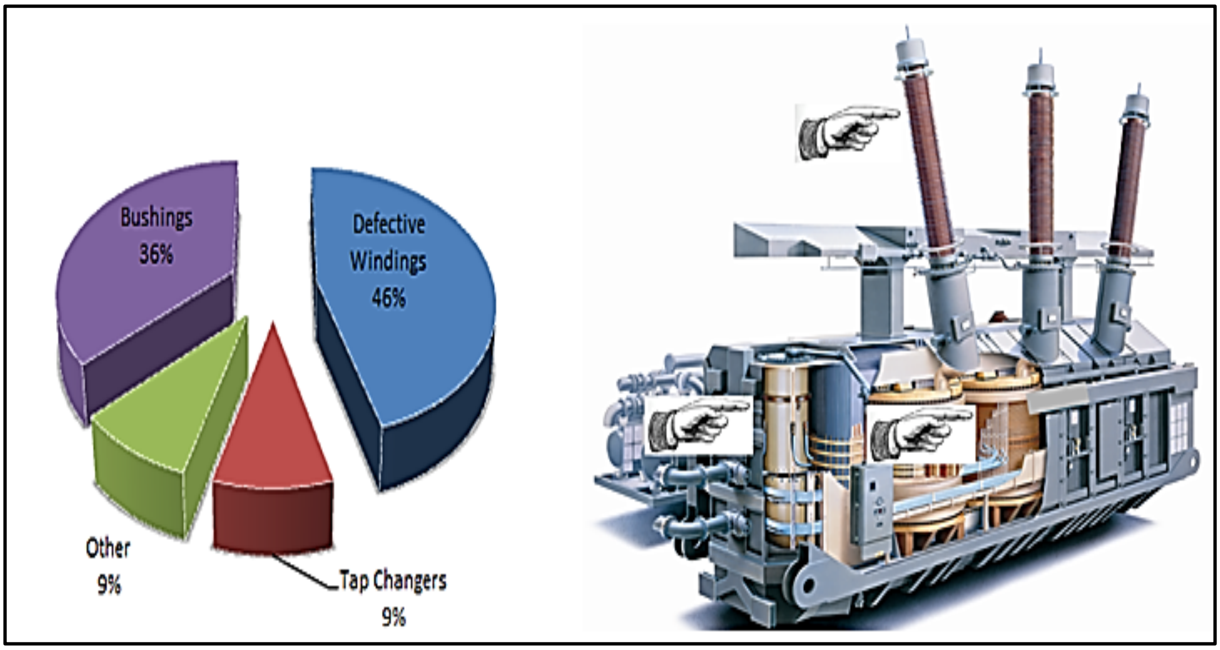


Figure 2.1: Frequency of the power transformer failure modes in Eskom Distribution [5]

2.3 Online Condition Monitoring Technology

Transformer online condition monitoring has been the subject of significant research and development over the past few years. Advances in technology now allow significant quantities of data about the operating condition and health of a transformer to be collected and analysed. Some of the available information is of use throughout the life of the transformer. For example, monitoring certain temperatures and the cooling state of a transformer will allow a continuous assessment of its overload capability to be made.

Some more sophisticated monitoring techniques, however, have a cost and complexity that perhaps make them more suitable for deployment at a stage in the lifetime of the transformer.

When a fault is suspected or has been detected by another means, an accurate analysis of what the problem is, where it is and what the diagnosis for the transformer, is required. For both these ends of the monitoring spectrum, and for the many applications in-between, it is becoming increasingly important to apply easy and safe monitoring of a transformer at any level and any point in its lifetime [8].

The online condition monitoring offers measurement analysis for most of the important parameters of the transformer condition. The following groups of operating parameters can be monitored continuously:

- cooling (e.g. fans, pumps, motors, etc.);
- on-load tap changer (e.g. taps positions, operations, contact wear, etc.);
- transformer operating temperatures (e.g. ambient, oil, winding, etc.);
- dissolved gas analysis (e.g. IEC Duval, IEE key gas, Etra, etc.);
- transformer ageing and loss of life (e.g. operating hours, overloading, etc.); and
- bushings (e.g. capacitance, tan delta, operating voltages, etc.).

2.4 Online Condition Monitoring technology and parameters

Over the past few years many transformer monitoring techniques and systems have been developed, offering a variety of advantages for the transformer operator and asset manager. These advantages range from the ability to know the overload capability of the transformer, to detailed monitoring of faults in the active part and accessories such as bushings and tap-changers.

The cost and complexity of monitoring systems vary greatly, and the application of all the available techniques to all transformers from new is not financially justified. Instead a mix-and-match approach is more likely to be appropriate, with the customer able to choose which type of monitoring is most appropriate, depending on the importance and health of the transformer. For example, it may be decided that monitoring cooler operation is important from new, but monitoring partial discharge is only worthwhile when a problem has been detected by using routine dissolved gas analysis.

This research study therefore sets out in what is intended to be sufficient detail to form the basis of a specification, which sensors and facilities are necessary or desirable on a transformer to allow most, if not all condition monitoring systems to be applied. There is an increasing capability within substation control and data systems to directly collect data relevant to transformer condition without the need for specific condition monitoring hardware.

This can potentially provide a path to implementing basic condition monitoring functions, but the relevant data must be available from the appropriate sensors. During this research, sensors will be installed to sense transformer parameters to provide the data. In many cases, the effective installation of a monitoring system requires the provision of a suitable communication link for alarms to be transmitted to the system operator or maintenance organisation. Where this is done via a substation control system, it is recommended that suitable provision is made for the communication of monitoring information, even if a monitoring system is not fitted initially [9].

Transformers play a key role in power plants, distribution networks and industries. It is therefore all the more important to continuously record and monitor their key parameters. However, individual sensors only provide a part of the overall picture. For this reason, a monitoring platform is needed to integrate and jointly analyse data from all different kinds of sensors. It allows measures for trouble shooting and repair to be planned and scheduled in advance, which means greater availability and a longer service life for transformers. [10]

Power transformers are the most expensive single elements in distribution networks. Therefore, it is an aim of the utilities to decrease the transformer life cycle costs, and to increase the usable service life. One possibility being in discussion today is the extension of the well-known classical method of transformer supervision by an advanced monitoring concept. To meet the expectations, a transformer monitoring system has to fulfil numerous requirements. Basic prerequisites are its suitability for long-term operation and sufficient reliability.

The installation and operating costs of a monitoring system have to be in reasonable relation to its benefits. A transformer monitoring system should provide information for a more reliable estimation of the remaining lifespan of the transformer. Furthermore, it should support the introduction of condition-based maintenance and help to avoid unexpected outages.

Beyond this, online information about the transformer is useful to estimate the overload reserve at any time. Knowledge about the previous operation condition allows a better interpretation of DGA.

For the creation of a transformer monitoring system, parameters have to be found which can be measured at the transformer and interpreted in order to obtain the desired information. Recording and storage of these measured values must be done in such a manner that they can be interpreted by the user or engineers. Furthermore, the recorded data must be available even after a number of years for data analysis and trending purposes. The main aim of a modern monitoring strategy is to record the relevant stresses that affect the ageing and all measured variables that characterise the condition of a transformer in combination with modern data acquisition, data processing and data transmission systems [11].

There are changes in the insulation system due to thermal, dielectric or mechanical impact. These changes result in a reduced insulation quality, e. g. degradation, local faults and breakdowns, ageing by hot-spots, etc. Generally, none of these deficiencies can be detected by one single method, nor can it be guaranteed that detection is successful by using any of the known diagnostics methods [8].

The advantages of transformer online condition monitoring can be summarised as follows:

- being able to obtain a comprehensive view of the current status, operating trends and signals received from transformers;
- faults can be detected early and correct decisions can be taken on a safe basis;
- information is available for the economical use of maintenance measures to extend the service life;
- it opens the possibility for extending the operating time of power transformers;
- reduced risk of expensive failures;
- provides potential for changing the maintenance strategy;

- provides assistance and guidance on indicating the type of fault in the transformers; and
- the ability to predict transformer failure before it occurs.

Transformers play a key role in power plants, transport and distribution networks, and industries. It is therefore important to continuously record and monitor their key parameters. However, individual sensors only show part of the overall picture. Online monitoring systems deliver a valuable contribution for early detection of malfunctions, general gathering of condition information, and for diagnosis.

The online condition monitoring allows for transformer condition assessment without having to switch off the transformer, thereby minimising power supply interruptions. The online condition monitoring system is a unique technology that monitors the condition of various parameters of the power transformer such as cooling fans, on-load tap changer, bushings, transformer operating temperatures, dissolved gas analysis, transformer ageing and loss of life.

2.4.1 Cooling fans

The cooling equipment collects hot oil at the top of the tank and returns cooled oil lower down on the side. The cooling arrangement can be seen as the two oil circuits with an indirect interaction, one inner and one outer circuit. The inner circuit transfers the loss of energy from heat producing surfaces to the oil. In the outer circuit the oil transfers heat to the secondary cooling medium. The ambient air normally cools transformers.

It is possible to build air coolers with forced air circulation more compactly than coolers with natural draught. However, such air coolers have a fairly high impedance to the oil circulation in the internal circuit, which necessitates that the oil be pumped through the cooler. For built-in transformers, deep underground power caverns, or in some industrial applications oil to water heat exchangers are used. In such cases, sufficient air for cooling may not be available. The system also permits small physical dimensions. The disadvantage of the compact design is that auxiliary power must always be available [12].

The examples below are different types of cooling together with special designations:

- ONAN: Oil Natural Air Natural;
- ONAF: Oil Natural Air Forced ;
- OFAN: Oil Forced Air Natural;
- OFAF: Oil Forced Air Forced; and
- OFWF: Oil Forced Water Forced.

A given transformer can have a combination of cooling types to permit a change in the type of cooling, e.g. ONAN/ONAF, etc. Pumps as well as fans sometimes suffer breakdowns. It must be possible to exchange such components without emptying the transformer or even taking it out of service. All cooling circuits should therefore be provided with necessary valves for shutting off each separate oil circuit.

For the larger units it is possible to suspend fans below or on the side of radiators to provide a forced draught and achieve an ONAF cooling arrangement. This might enable the transformer loading to increase by approximately 25%. The radiators have to be grouped in such a way to obtain coverage by the fans [13].

Factors that influence temperature are as follows:

- ambient temperature, temperature rise by resistance;
- temperature gradient between inlet and outlet;
- difference between maximum and average gradient; and
- mounting height of the radiator.

The research study will only focus on the ONAF cooling method. As illustrated in Figure 2.2 below, the cooling radiators have externally mounted fans. Blowing air through the radiators ensures a better heat transfer, as the hot air next to the radiators is forcibly replaced by cooler air. Normally, the fans are fitted below the radiators and blow surrounding air vertically upwards between the radiators, as illustrated in Figure 2.2. A further advantage of ONAF is that, in periods of low load or low ambient temperature, the fans need not be running. Fans are normally activated by a contact on the winding temperature gauge. The typical temperature setting for fan activation is 65° C [13].

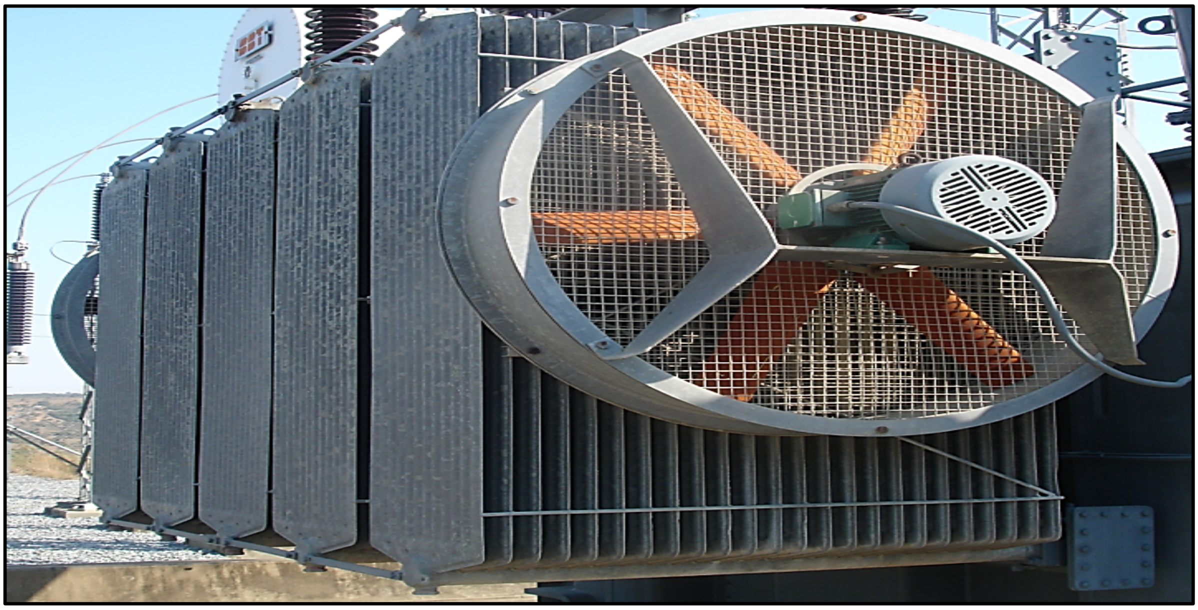


Figure 2.2: Example of ONAF cooling method (fan) in a transformer

The measurement of fans and pumps current is necessary to verify the correct operation of each fan and pump group. Online condition monitoring offers measurement analyses for cooling system monitoring of the transformer condition.

The online condition monitoring will monitor the following parameters for the cooling system:

- operating state of the pumps and fans;
- operating times of the pumps and fans; and
- cooler efficiency monitoring.

2.4.2 On-load tap changers for transformers

In the case of power transformers used for substation distribution purposes, the primary voltage may be reasonably constant, but the secondary voltage varies due to fluctuating load at different times of the day.

This voltage needs to remain as stable as possible to ensure that customer distribution transformers down line maintain a constant voltage on their secondary side. This is obtained by using voltage monitoring relays that automatically raise or lower the secondary voltage on the transformer by means of an on-load tap changer. The majority of all transformers incorporate some means of adjusting their turns ratio, by adding or removing tapping turns.

The on-load tap changer has to provide uninterrupted current flow during the transition operation from one tap to the other. The current flow must be maintained uninterrupted without partial short circuiting of the tapped winding. As early as between 1905 and 1910 arrangements were introduced for a changeover between tappings of the transformer without interruption of supply [14].

The operation of an on-load tap changer can be understood by two identifiable functions. It implies a switching device that transfers the throughput power from one tap of the transformer to an adjacent one. During the operation the two taps will be connected through the fitted transition impedance. In this phase the two taps will share the load current. After connection to the transformer tap, the load will be interrupted and transferred to the new tap. The device that performs this switching is known as a diverter switch.

The connections of the two taps that involve the diverter switch may be transferred one position along the series of physical taps of the regulating winding of each operation. This is a tap selector switch. Refer to Figure 2.3 for an example of a tap change drive mechanism. Visible at the bottom is the control cable. Visible at the top is the tap change drive shaft.

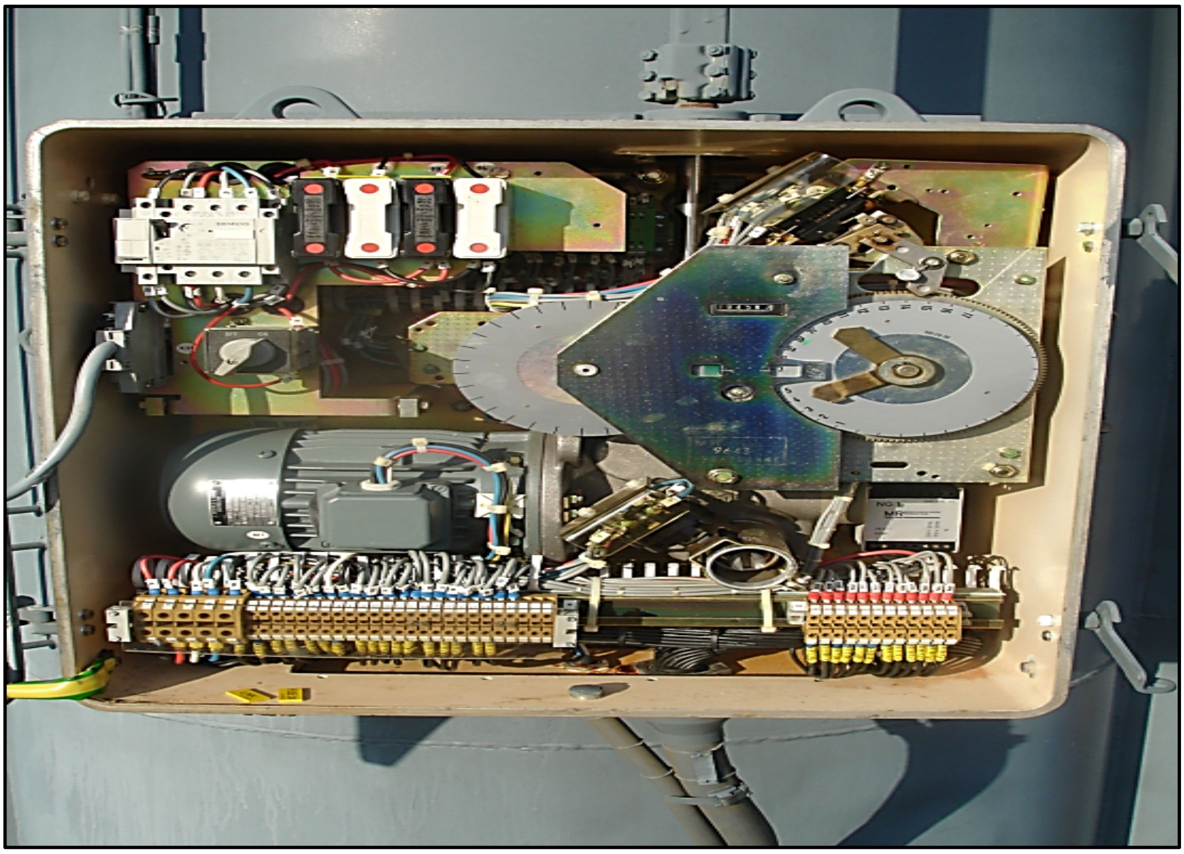


Figure 2.3: Typical example of a tap change drive mechanism

A properly functional tap changer is necessary in almost every power transformer. The online condition monitoring provides several measured values such as temperatures, currents, tap position and tap changer operations. Due to these values, malfunctions of the tap changer can be detected.

The electricity industries are experiencing numerous failures of tap changers in their fleet of transformers. Online condition monitoring of tap changers is imperative to prevent destructive failures. It will improve the performance of tap changers, reduce contact wear and prevent premature failure of the tap changer and hence the transformer [15].

Tap changer monitoring supports the early detection of mechanical faults and the condition-based maintenance of the switch contacts.

The online condition monitoring will monitor the following parameters for on-load tap changers:

- tap position, number of switching operations;
- power consumption of motor drive, contact wear (approximated);
- oil temperature, tap-changer compartment; and
- oil temperature differential, tap-changer compartment – main tank.

2.4.3 Transformer operating temperatures

The insulation of a transformer tends to age and deteriorate when heated. The higher the temperature, the faster the insulation deterioration. During periods of subnormal operating temperature, the loss of life of the insulation is slower than normal. However, when the operating temperatures are greater than normal, the loss of life will be higher than normal. Consequently, transformers may be safely operated for a time at above normal temperatures, provided that the loss of insulation life during this period is adequately compensated for by operating for a long period at temperatures lower than normal.

Most of the transformers are provided with oil temperature indicators (OTI) for measuring hot top oil temperature of a transformer. Winding temperature indicators (WTI) are also used to give an idea of the winding hot-spot temperature by means of a thermal image method. Typical values used by utilities are oil temperature alarm 85°C, and oil temperature trip 95°C [13].

The oil temperature of a transformer is affected only gradually by internal heat dissipation, whereas the winding temperature reaches its steady state considerably faster due to a sudden increase in load. The thermal time constant for the windings is determined in minutes, but amounts to several hours for the oil. The winding temperature trip will only trip the low voltage breaker, as the temperature is load related and not an internal fault on the transformer. In cases where transformers are ONAF, a third switch will start cooling fans mounted on the transformer cooling fins. Typical values used by utilities are: cooling fans start at 65°C, winding temperature alarm 100°C, and winding temperature trip 120°C [13].

The load capability of power transformers is limited principally by the winding temperature. However, the true limiting factor is the hottest winding section, since the winding temperature is not uniform over its extent. This section is known as a winding hot spot, and it is located around the top of the winding. The hot spot temperature may be determined by a mathematical model with ambient temperature, top and bottom temperatures and the load current as inputs.

The hot spot monitoring is taking advantage of cold ambient temperature to extend the transformer’s lifetime, providing the capacity of urgent overload. The online condition monitoring offers measurement analysis for transformer operating temperatures. The online condition monitoring will monitor the following parameters for transformer operating temperature systems:

- top oil temperature, bottom oil temperature; and
- control cubicle temperature and ambient temperature.

2.4.4 Dissolved Gas Analysis

Dissolved Gas Analysis (DGA) is the most acknowledged fault diagnostic method widely applied for detection of incipient or potential faults, and thus for assessment of transformer condition. Within an effective oil analysis programme, oil sampling, sample storage, analysis and interpretation techniques play significant roles to ensure reliable diagnosis of oil filled power transformers [16].

DGA is a very useful diagnostic tool and is universally applied for condition assessment of power transformers. The gases that are normally measured are Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Oxygen (O_2) and Nitrogen (N_2). There is no consensus about the absolute maximum levels that are acceptable for each gas [16].

Furthermore, several tools have been developed for the interpretation of DGA results. The early valuable works of Rogers and Doernenberg [16] use the ratios of certain gas concentrations to match the DGA gas profile to typical sources of gas generation, as well as the level of energy involved [16].

For example, the ratios help to discern whether the gas profile is the result of:

- thermal fault of low, medium and high temperatures; or
- discharges of low and high energy, and partial discharge.

The ratio method is also discussed and utilised in IEC 60599 “Guide to Interpretation of Dissolved and Free Gas Analysis”. The work of Duval provides another tool for the interpretation of DGA [16].

2.4.4.1 IEC Duval

In Duval's triangle method, developed by Michel Duval [16], only three gases namely CH_4, C_2H_4 and C_2H_2 are used. It is the graphical representation of fault determination. The Duval Triangle represents three types of faults, for example thermal faults in various ranges, low and high energy densities and partial discharge. Figure 2.4 below shows the graphical representation of the Duval triangle.

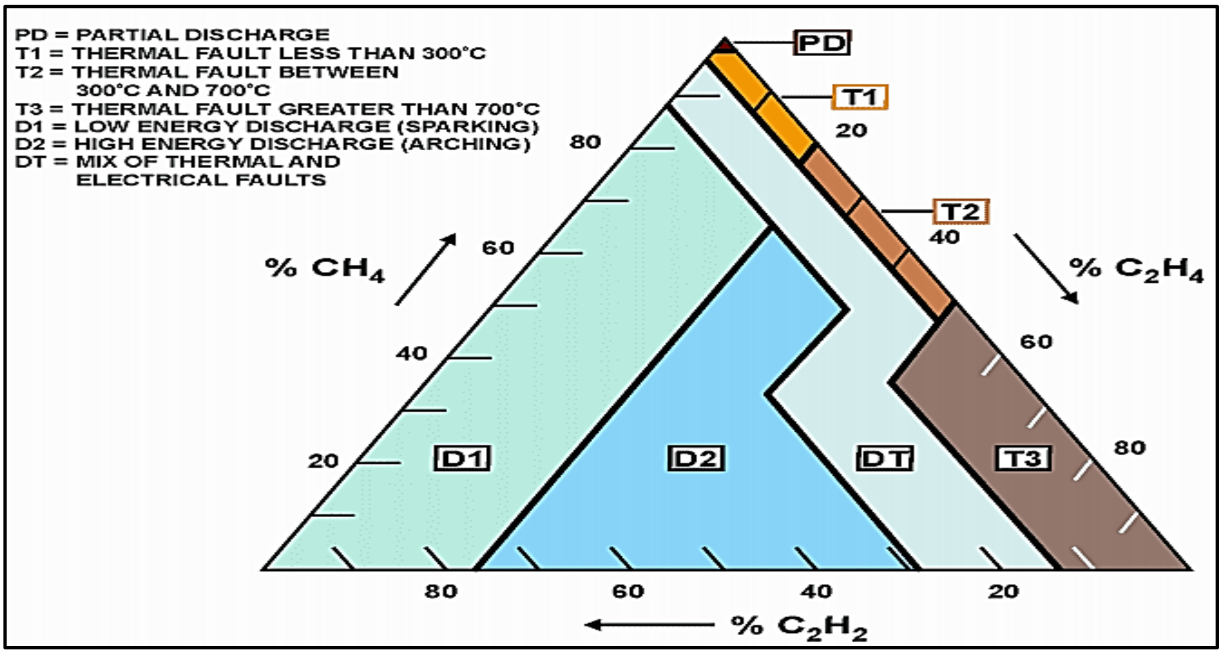


Figure 2.4: Duval DGA Interpretation [16]

2.4.4.2 IEEE keygas

IEEE Keygas uses gases which are typical or predominant at various temperatures. These significant gases and proportions are called "key gases". The key gas method uses the individual gas rather than the calculation of gas ratios for detecting faults. Furthermore, this method represents some predefined relative gas concentration charts that indicate four general faults:

- overheated oil;

- overheated cellulose;
- corona in oil (PD); and
- arcing in oil.

2.4.4.3 IEEE Rogers ratios

For the Rogers ratio method only the three basic ratios C_2H_2 / C_2H_4, CH_4 / H_2 and C_2H_4 / C_2H_6 are used. This method is based on the thermal degradation principles and diagnoses the faults conditions as thermal and electrical faults in the following categories:

Table 2.2: IEEE Rogers ratios (diagnose description) [18]

	Meaning
PD	Partial discharge
T1	Thermal fault < 300°C
T2	Thermal fault 300°C – 700°C
T3	Thermal fault > 700°C
D1	Discharges of low energy
D2	Discharges of high energy
DT	Combination of thermal fault and discharges

2.4.4.4 IEEE Doernenburg

The Doernenburg ratio method differentiates between thermal decomposition and electrical faults with high or low energy by using four ratios: CH_4 / H_2, C_2H_2 / C_2H_4, C_2H_2 / CH_4 C_2H_6 /

C_2H_2). In order to apply this method, at least one gas for each of the ratios must exceed the corresponding concentration.

Table 2.3: IEEE Doernenburg (diagnose description) [17]

	Maximum gas concentration
Hydrogen (H_2)	100
Methane (CH_4)	120
Carbon monoxide (CO)	350
Acetylene (C_2H_2)	1
Ethylene (C_2H_4)	50
Ethane (C_2H_6)	65

2.4.4.5 Electric Technology Research Association (ETRA)

This method is based on DGA diagnostic algorithms published by the Electric Technology Research Association (ETRA) in Japan in 1999. The ETRA method provides two graphical representations for fault diagnosis (Chart A and B). Through both charts an improvement in diagnostic precision is expected. Diagnostic chart A is based on the two ratios, C_2H_4 / C_2H_6 and C_2H_2 / C_2H_4. Those are useful for distinguishing between overheating and discharge phenomena.

In diagnostic chart B the discharge domains are separated into three parts by using ratios: C_2H_4 / C_2H_6 and C_2H_2/ C_2H_6. They are:

- arc discharge (high energy);
- discharge (middle energy); and
- partial discharge (low energy).

Table 2.4: IEEE Etra A (diagnose description) [17]

	Meaning
A	Discharge
B	Overheating above 700°C or overheating with discharge
C	Overheating below 300°C
D	Overheating 300°C – 700°C
E	Overheating above 700°C

The main sources of dissolved gases in the transformer oil are thermal and electric in nature, and generally relate to a minimum level of disturbance. Usually, fault gases are associated with continuous gas generation (relative increase) and to certain absolute levels that are indicative of a problem. Results are confirmed by laboratory investigations. Integrated online condition monitoring allows for transformer condition assessment without having to switch off the transformer, thereby minimising power supply interruptions. The integrated online condition monitoring system is a unique technology that monitors the condition.

The online dissolved gas analysis benefits are the following:

- detection of transformer faults in their infancy, before irreparable damage is done;
- reduced probability of unplanned outages and/or risk of catastrophic failure;
- lower inspection and maintenance costs, by switching to condition-based maintenance; and
- no consumables. No carrier or calibration gases management and logistics requirements.

2.4.5 Transformer ageing and loss of life

"Ageing" can be defined as a process that causes change in equipment properties as the equipment is exposed to stresses. The change in equipment properties is likely to affect its performance against its intended function. Ageing is a result of stresses being applied on equipment. These stresses can be electrical, mechanical or environmental. Stresses can be normal or abnormal.

Normal stresses are those that are within the equipment's rated parameters and defined service conditions. This includes short-term overload, where the short-term overload is a rated parameter defined for the equipment by the manufacturer. Abnormal stresses include conditions that are beyond the rated parameters of the equipment or the defined service conditions [18].

The isolation temperature is the main cause of transformer ageing. The cellulose isolation undergoes "depolymerisation", caused by temperature and time. As the cellulose chain becomes smaller, the mechanical properties of the paper such as traction resistance and elasticity are degraded. It is possible that the paper becomes fragile and is incapable of withstanding the short circuit forces and the normal vibrations. This is pointing towards the end of the life of the solid isolation, thus determining the end of transformer life.

A transformer has practically no moving parts, except tap changers or cooling fan or pump motors. Therefore, it cannot wear out like rotating machinery. With adequate protection against corrosion, the copper windings, laminated cores and fabricated parts will last indefinitely. But insulating materials, mostly made from cellulose materials, deteriorate from the effects of temperature, moisture and oxygen. Out of these factors, it is the temperature which must be kept within known limits to prevent rapid deterioration of insulation [19].

The life of a transformer is normally dependent upon the life of the insulation. When insulation fails, the transformer life has ended. The term transformer life gives an impression that it was quite definite, but in fact a transformer hardly ever dies. It is usually killed by some unusual stresses breaking down a weakened part, leading to the end of the transformer.

The two factors which normally contribute to the eventual failure are:

a. deterioration of insulation over a span of time with temperature, moisture and oxygen; and
b. operating stresses - mechanical, electromagnetic and thermal - beyond the strength of those parts which have considerably weakened over a period of time.

To extend the life of a utility's aging power transformer fleet, keen attention must be given to the testing, analysing and trending of this crucial substation equipment. The data obtained from testing, monitoring and inspecting the power transformer should be used not only to diagnose but also to predict developing internal faults before they lead to catastrophic failure of the power transformers. The online devices and software that monitor the transformer oil are among the new technologies and diagnostic techniques being employed to effectively manage the life cycle of power transformers [19].

Online condition monitoring monitors the following parameters for transformer ageing and loss of life:

- transformer lifetime estimation and ageing rate;
- load current, voltage and load factor;
- all secondary protective devices monitoring (e.g. oil level, Buchholz, pressure relieve valve, oil temperature indicators and winding temperature indicators);

- overload capacity, overload 24h forecast, actual losses, transformer efficiency; and
- cooling state.

2.4.6 Bushings

Power transformer bushings are among the least reliable components in high voltage systems, therefore the knowledge of their wear condition is very important for proper network management. It is well known that transformers are fundamental parts of electrical power systems, and a considerable amount of their failures is caused by their bushings. Bushings are insulated bars made of conductive materials allowing the connection between transformer and power lines.

One of the most common types for high voltage applications is the Oil Impregnated Paper (OIP) bushing. Bushings are usually equipped with a test tap which can be employed for diagnostics purposes. The most common method consists of measuring the impedance between the power conductor, the tap and the flange of the bushing.

In recent years, particular attention has been paid to reduce as much as possible the temporary out of service of power systems due to malfunctions or failures of their components. In order to achieve this goal, several diagnostic techniques have been developed. These methods are particularly effective when they allow the continuous monitoring of components during normal operation, and to estimate their time to failure.

An effective schedule of the maintenance activity is thus possible, since the components can be replaced before their failure with minimal impact. As already indicated, transformers are fundamental parts of the electrical power systems, and a considerable amount of their failures can be contributed to their bushings [20].

The risk of major failures caused by bushings in general is 29% but 37% out of 29% results in fire. Bushings are insulated bars made of conductive materials allowing the connection between transformer and power lines. One of the most common types for high voltage applications is the OIP bushing. Bushings are usually equipped with a test tap which can be employed for diagnostics purposes. The critical method used is measuring the impedance between the power conductor, the tap and the flange of the bushing [21]. The basic construction of a power transformer bushing is shown in Figure 2.5 below.

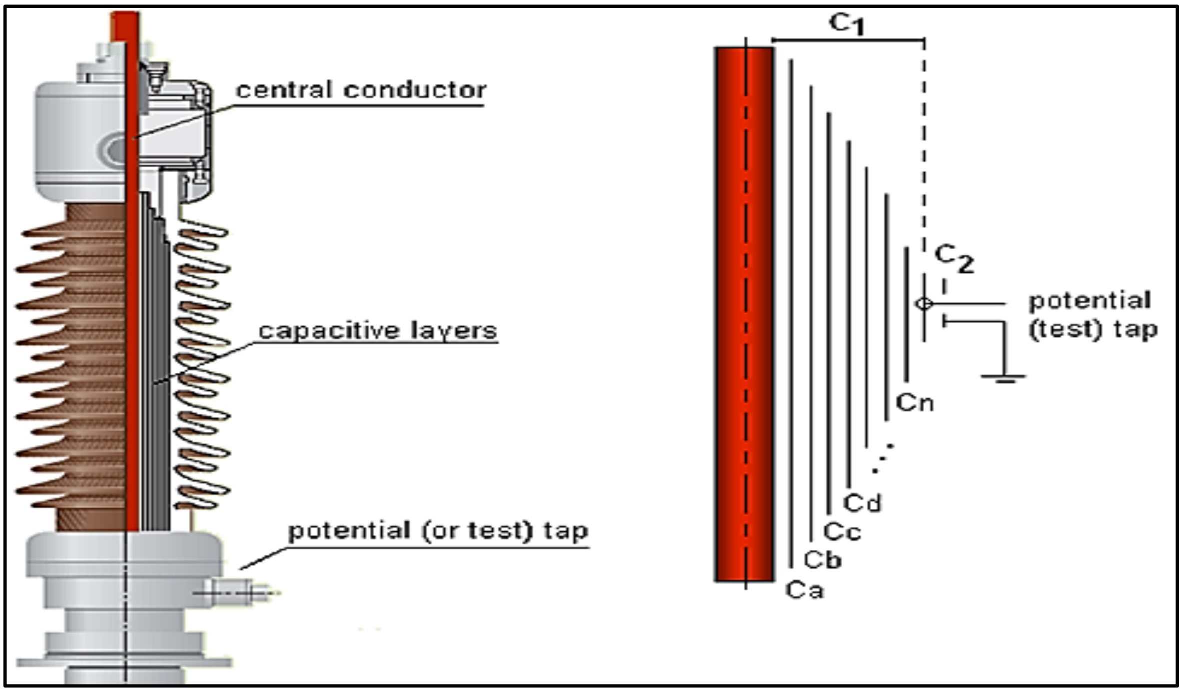


Figure 2.5: Power transformer oil impregnated paper bushing construction [40]

Measuring the capacitances and their dissipation factors allows one to infer the wear status of the bushing. This is usually performed by switching the transformer off where test taps are available, or by removing the bushing from the transformer where test taps are not available, thus putting some lines out of service.

It is clear that an online measurement of these parameters would provide a huge advantage in terms of safety, cost and efficiency. For this reason, several bushing monitoring methods have been developed during the last decade [22] - [24]. Most of the bushing failures result in fires, damaging the equipment as shown in Figure 2.6 and Figure 2.7 below.

Figure 2.6: Failed exploded bushings resulted in a fire

Figure 2.7: Failed exploded bushings resulted in a fire

Bushing failures usually occur in a sequence of small defects which impose the loss of intermediary capacitive layers, frequently caused by short circuit between two conductive aluminium sheets. This progression is irreversible and provokes the elimination of one capacitive layer, thus causing an increase in the overall capacitance of the bushing. By monitoring the voltage or current on the capacitive tap (voltage or test tap) of the bushings, it is possible to verify the variation on the capacitance relative deviation between the phases, and to identify a possible fault. The online condition monitoring will monitor the following parameters for transformer bushings:

- AC leakage currents of fundamental harmonic;
- phase angle between currents of adjacent phases;
- magnitude and phase angle of imbalance of three connected Y-connected bushings;
- phase and transformer comparison; and
- sum of current reference and test and alarm generation.

2.5 Online Condition Monitoring optimisation studies

With a high energy demand and failure rate of power transformers on the increase, the sudden failure of a large transformer may cause an interruption in power supply, resulting in high repair costs, revenue losses as well as environmental and collateral damage. Therefore, it is an aim of the utilities to decrease the transformer life cycle costs, and to increase the usable service life. Several online condition monitoring of power transformer technology optimisation techniques or methods based on cost and performance were studied, as discussed in the following sub-sections.

2.5.1 Cost optimisation

A cost or benefit analysis for a monitoring system requires hypothesis of many individual parameters that are difficult to assess. For a general approach, not all of these items can be calculated exactly. However, in all cases, the prevention of major failures can be counted. The other savings have to be taken into account depending on the specific situation.

Pertaining to the prevention of failures and downtimes, this covers the cost benefits achieved by the avoidance of failures and downtimes of the transformer itself. These so-called strategic benefits are based on the ability to prevent major failures and avoid collateral damages. The financial benefits are increasingly positive for the avoidance of collateral damage and savings where transformer online condition monitoring technology is used for the complete transformer population.

Direct benefits are cost savings achieved by reducing the number of spares to be kept, as the required stock level is a function of failure rate. Additional spare transformers equate to additional transport, rigging and eventually maintenance at the stores. Thus, keeping spares will result in savings in the costs of transporting spares from one operating unit to another over the longer distances. This also affects restoration times.

The cost savings will be achieved in the utilities, as no penalties will be imposed as a result of prolonged outages to the key customers as per contract obligations. The cost savings from utilities insurance premiums will be low because claims from customers will be less, and environmental transgressions incident rates will be low, since transformer failures will not take place.

2.5.2 Performance evaluation

The justification for online monitoring of power transformers is driven by the need of the electrical utilities to reduce operating costs and enhance the availability and reliability of their equipment. The evaluation of data acquired by an online monitoring system shows the capability to detect oncoming failures within active parts, bushings, on-load tap changers and cooling units. Using the benefits of modern information technology, the distribution of information regarding the condition of the equipment can easily be done by means of standardised web browser technology or local area networks.

When considering the installation of online monitoring systems size, importance and condition of a power transformer have to be analysed. These applies especially for aged transformers, and in general for strategic locations in the electrical network, where online monitoring is necessary and valuable, as the prevention of major failure costs will result in a reduction in costs for outages, transportation, repair, consequence of failures and associated collateral damages. The online monitoring system appears as a useful tool to achieve the aim of improving assets availability and reliability.

This equipment may assist in preventing a failure, or give precise and instantaneous information about the real condition of a transformer with an incipient failure that, for some reason, must be in service until repair works can be done or a spare is available. These values are continuously monitored, and if there is a change, it will be prompted in the control room of the power station and directly communicated by e-mail or short message system (SMS) to technical staff in order to take some action, if needed.

2.6 Conclusion

A global review of relevant online condition monitoring literatures for power transformers, as well as the technologies involved, was presented in this chapter. Many developmental studies based on efficiency improvement of power transformer failures have already been conducted. There is a lack of applications and studies demonstrating the technical, economic and environmental benefits offered by the online condition monitoring technology.

Moreover, there are no studies demonstrating the optimal usage of transformer online condition monitoring technology in South Africa. This hinders the deployment of online condition technology in power transformers. South Africa has a considerable number of power transformers installed in the network.

Over the past few years various transformer monitoring techniques and systems have been developed, offering a variety of advantages for the transformer operator and asset manager. These advantages range from the ability to know the overload capability of the transformer, to detailed monitoring of faults in the active parts and accessories such as bushings, cooling units, active parts and tap changers. The cost and complexity of monitoring systems vary greatly, and the application of all the available techniques to all transformers is not financially justified.

This chapter also emphasised that different online condition monitoring applications are available worldwide, as well as technologies involved. It has been found that locally, there is a lack of online condition monitoring applications in power transformers, since many people are unaware of this technology.

This chapter also presented different parameters of online condition monitoring to be used in power transformers. It is important to make the right selection for a specific application. Thus, the benefits and drawbacks of different parameters of online condition monitoring to be used in power transformers were also presented in this chapter.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter discussed the research methodology used in the study. The main problem researched is restated along with the data collection, measuring tools and limitations of the study. The continuity of supply is a requirement for the selected distribution substation, and the site has been selected because of the power transformer failures it has experienced previously. The proposed online condition monitoring technique will assist in preventing the probability and consequences of power transformer failures. The online condition monitoring data of power transformer parameters of the selected site will be logged and analysed.

3.2 Data collection

The data collection methods used include a literature review, measured and calculated data. The analysis will be conducted via the sensors installed in the transformer to monitor various parameters of the power transformer such as cooling fans, on-load tap changer, bushings, transformer operating temperatures, dissolved gas analysis, transformer ageing and loss of life. The data will then be transferred to the server via fibre optic cable communication.

The online data will be incorporated into a database and integrated with offline values previously configured on the system (transformer profile, parameters, limits, etc.). The data analysis performed is based on acquired data processed by the engineering models in order to assess possible deviations from normality, and to determine the significance of such deviations. The treatment of transformers by age is a matter of the owner's internal policy. The age of a transformer can have a number of effects, including affecting the mechanical strength of the transformer's insulation, and hence its ability to withstand common short circuit forces that are inherent in a power system. A further consideration is the relationship between advanced paper aging and transformer age. The relationship between the age of the transformer and its performance is a subject of great uncertainty.

However, coupled with the other factors listed here, the transformer's age can play an importance role in risk decision. It is common knowledge that transformers built and designed in the past have proven to be highly reliable with a low failure rate for many decades. The age distribution for transformers clearly indicates an aging transformer population. There are 65 units over 40 years old which counts for almost one third of the population in the Northern Cape Operating Unit (NCOU). Figure 3.1 below gives the age distribution of all the transformers in service for NCOU.

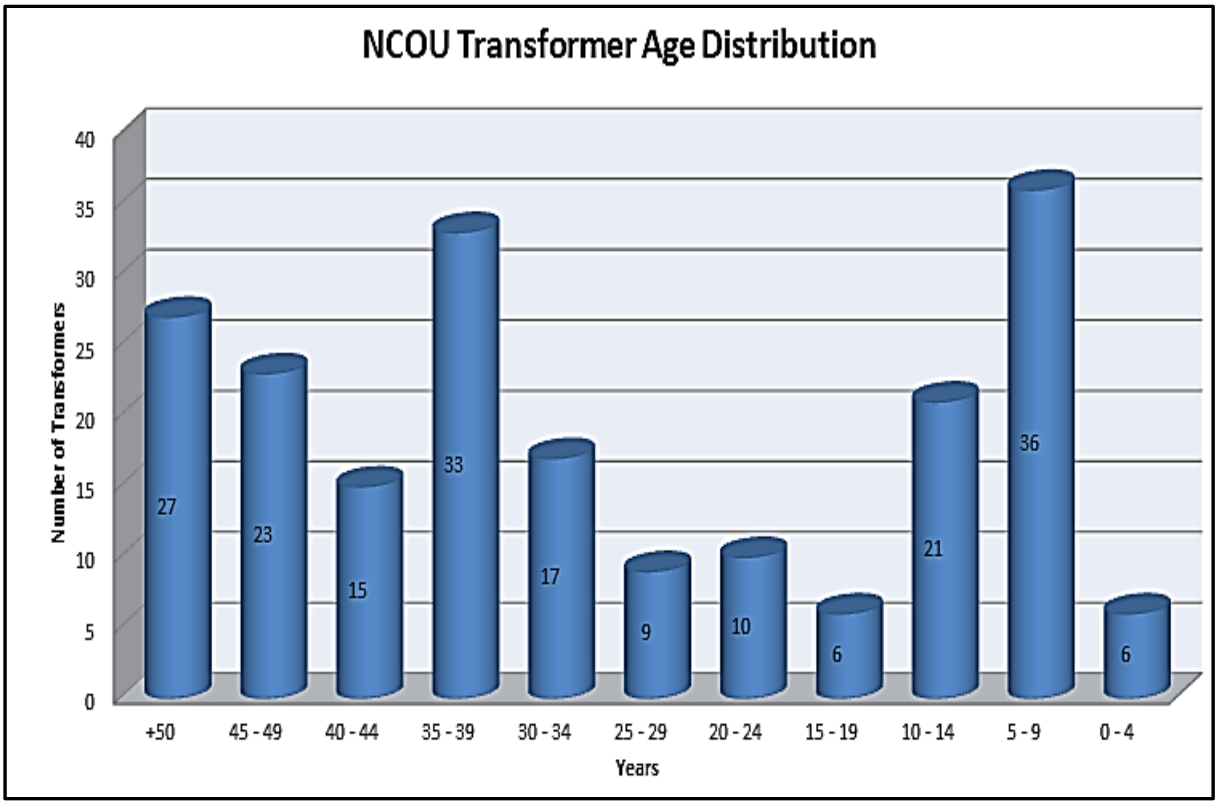


Figure 3.1: The age distribution of all the transformers in service for NCOU

The online data technology monitor also correlates the present value of a given variable (or acquired parameter) to its historical behaviour which is duly stored in the database. In case a deviation is detected and a significant level of importance is also attributed to the parameter by online data technology monitor expert knowledge, the user is notified of such an occurrence. Before sending an alarm message, however, an online data technology monitor implements a historical investigation of all possible correlated variables which could influence the observed deviation and also makes that correlation available to the engineers. Figure 3.2 below illustrates the data communication topology of online condition monitoring of power transformer to be adopted for this research study.

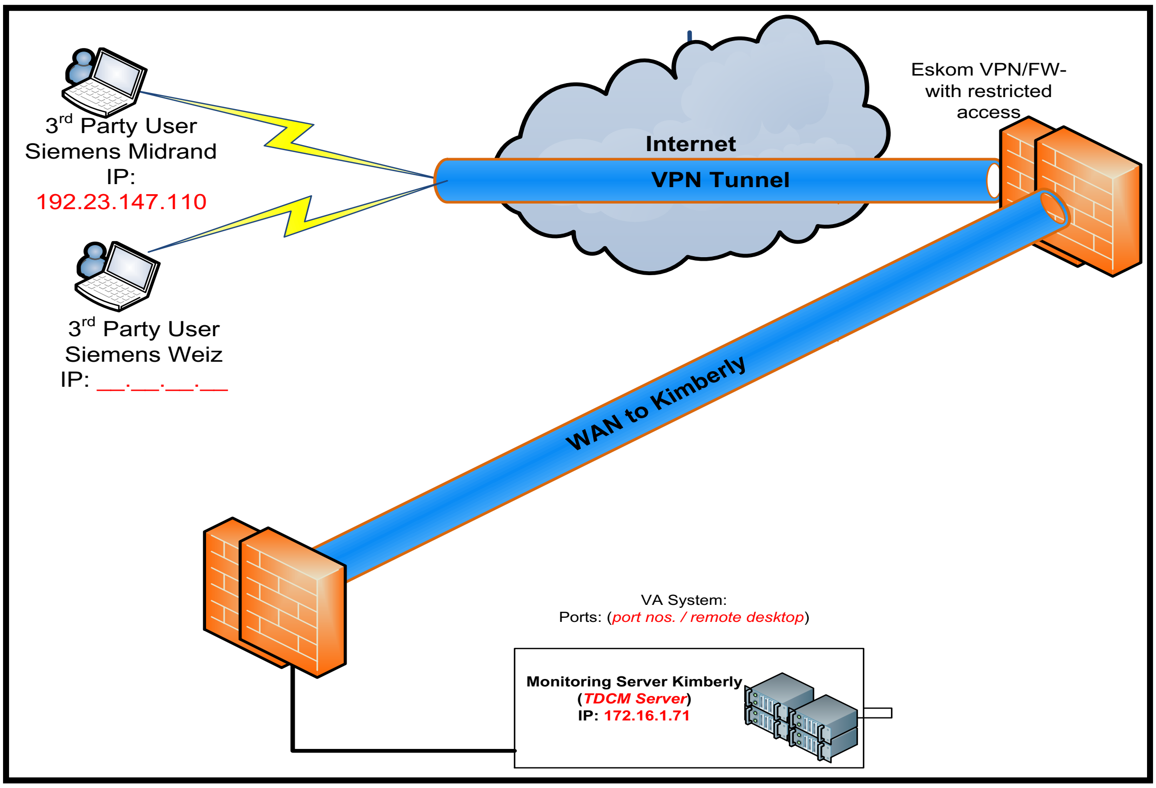


Figure 3.2: Data acquisition architecture for online monitoring in the research site

The advantages of this type of data collection are that the researcher has first-hand experience in case a deviation is detected, and a significant level of importance is also attributed to the parameter by online data technology monitor expert knowledge. The user is then notified of such an occurrence.

3.2.1 SITRAM condition monitoring

The results of the investigation were carried out on the equipment that have failed during operation. NCOU contributes to 1.96% of all the failures in the Eskom Distribution 12 Month Moving Average (MMA). It can be concluded that 46% of power transformers have their failure attributed to defective windings. The other reasons for transformer failures include 9% that has their failure attributed to tap changers, 36% that has their failure attributed to bushings, and 1% that has their failure attributed to “end of life”. It will be cheaper to monitor the power transformers than to wait for them to fail. Please refer to the graph below for a 12 MMA transformer failure rate for NCOU [1].

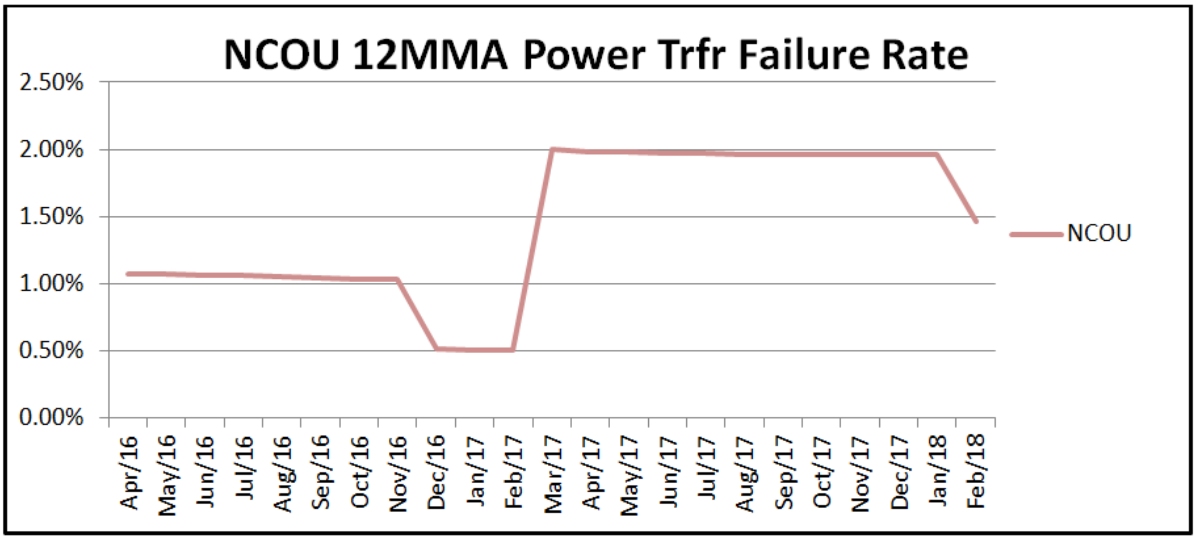


Figure 3.3: NCOU 12MMA power transformer failure rate [5]

The cost-effective technology that was utilised for this research study to assist in data collection to reduce the high number of power transformers failing is called SITRAM condition monitoring [10].

The SITRAM condition monitoring is comprised of standardised, proven online sensor technologies as standalone solutions for individual power transformers. Different kinds of warning instruments alert engineers if deviations develop that might lead to errors or unplanned outages [10].

The type of technology used in this research study is installed and tested in Africa for the first time. SITRAM condition monitoring is a modular system which integrates information from individual sensors, and other measuring devices such as a tap changer monitoring device, bushings monitoring system, or free dehydrating breathers for every transformer. The monitoring of limit values with a set of standard interpretation algorithms is a cost-effective way to keep an eye on essential transformer parameters. The measured values are stored locally in a data acquisition unit (Historian Server) and can be accessed remotely via modem communication interface, wide area network (WAN) and local area network (LAN) [2].

Various visual display systems are obtainable depending upon the organisations or utilities philosophy. Whether on WAN/LAN displays or web-based visualisations, the measured data can always be depicted in a user-friendly way, i.e. mathematical numbers, graphs, trends, etc. Whether it is in power plants, industrial plants or transmission and distribution networks, the strategic importance of every transformer demands individual monitoring to avoid catastrophic failures.

Figure 3.4: SITRAM condition monitor in a transformer [10]

Figure 3.4 above shows the transformer online monitoring cubicle installed recently in the research site at Kimberley Distribution Substation (KDS). The system allows continuous monitoring of the condition of the transformer bushings, tap changer, cooling fans, insulating oil and winding temperature, and gives warnings signs and trigger alarms should any of the parameters exceed set limits; and this therefore prompts preventative action to be taken before anything fails. Experience has shown that early detection of errors is simply not possible without online monitoring. It allows measures for troubleshooting and repair to be planned and scheduled in advance, which means greater availability and a longer service life for the transformers. The SITRAM condition monitoring can be interfaced with online gas analysers, partial discharge monitoring, bushing monitoring and tap changer monitoring.

3.2.2 Kelman TRANSFIX* 1.6E Online 8 Gas DGA Monitor

The stability of any distribution network is very much dependant on the performance of the power transformers. These transformers need to be monitored to ensure that any unwanted conditions, including high levels of certain gases, are detected. The oil acts as insulation as well as coolant for the transformer windings. It is very important to monitor the levels of different gases within the transformer tank, as they may assist with the indications of local faults, breakdowns and hot spots [23].

Knowledge of the condition of transformers is essential for all electrical networks, and online monitoring of critical transformers is increasingly vital. This information allows valuable assets to be maximised and expensive failures to be avoided. Dissolved Gas Analysis (DGA) and moisture measurement of the insulation oil are recognised as the most important tests for condition assessment of transformers. The cost-effective technology discovered for this research study to assist in collecting data for condition assessment of power transformers is called Kelman TRANSFIX* 1.6E Online 8 Gas DGA Monitor. Refer to Figure 3.5 for an example of a Kelman TRANSFIX* 1.6E Online 8 Gas DGA Monitor.

Figure 3.5: Kelman TRANSFIX* 1.6E Online 8 Gas DGA Monitor in a transformer [23]

The Kelman TRANSFIX 1.6E as illustrated in Figure 3.5 is an online DGA monitor offering added integrated functionality for further insight into the condition of transformers.

This equipment provides the following benefits to Asset Managers and Engineers:

- Detection of transformer faults in their infancy, before irreparable damage is done;
- Reduced probability of unplanned outages and/or risk of catastrophic failure;
- Lower inspection and maintenance costs by switching to condition-based maintenance; and
- No consumables. No carrier or calibration gases management and logistics requirements.

The Kelman TRANSFIX 1.6E is an online DGA monitor that offers the following features for dissolved gas analysis:

- Eight gas DGA plus moisture measurements;
- Reliable modified headspace gas extraction;
- Uses photo-acoustic spectroscopy to give highly reliable results. Field proven in over ninety countries worldwide;
- Discrete sampling gives more rapid response to gas rises. No ‘averaging’ of DGA results;
- Estimation of nitrogen and total gas content for free breathing transformers;
- Sampling rates are configurable from 4-weekly to hourly. Caution and alarm modes can be used to automatically increase the sampling rate;
- Provision for up to 8 inputs for direct measurement of winding temperature hot spots.
- Communication through Ethernet Transmission Control Protocol (TCP)/Internet Protocol and local area network (LAN) connection; and
- Two sunlight-visible front panel indicators (red & yellow) and two alarms relay contacts, each user configurable based on gas levels, moisture level or rates of change. The Kelman TRANSFIX* 1.6E Online 8 Gas DGA Monitor is interfaced with SITRAM condition monitoring to transfer a measured data to the monitoring server.

3.2.3 Bushing monitoring system

Power transformer bushings are among the least reliable components in high voltage systems, therefore the knowledge of their wear condition is very important for a proper network management. It is well known that transformers are fundamental parts of electrical power systems, and a considerable amount of their failures is caused by their bushings. Bushings are insulated bars made of conductive materials allowing the connection between transformer and power lines.

One of the most common types for high-voltage applications is the Oil Impregnated Paper (OIP) bushing and Resin Impregnated Paper (RIP) bushing. Bushings are usually equipped with a test tap which can be employed for diagnostics purposes. The most common method consists of measuring the impedance between the power conductor, the tap and the flange of the bushing [21].

Among the reasons for transformer outages, bushing failures rank considerably high. One reason could be that these bushings are usually tested offline to measure capacitance, dissipation factor and power factor. With the new online Bushing Monitoring System, it enables asset managers and engineers to check the condition of critical equipment such as power transformers, and reactors without having to shut down facilities first.

The asset condition data allow a thorough analysis and can reveal developing equipment issues before they become a problem. Therefore, maintenance work and repairs can be scheduled accordingly, maintenance downtimes and costs can be minimised, and adequate staff support can be provided to foster best service results. The bushing monitoring system can be used as a standalone system or in combination with a SITRAM transformer condition monitoring system.

It is always better to integrate multiple measurement results into an overall picture, rather than founding the analysis on measurements of individual sensors. The bushing monitoring system provides alarm set points, graphical displays and algorithm-based alarms that maximise response without triggering false alarms.

The bushing monitoring system is available in different versions with 3, 6, 9 or 12 bushing sensors, depending on individual requirements. The basic illustration of a bushing monitoring system is shown in Figure 3.6 below.

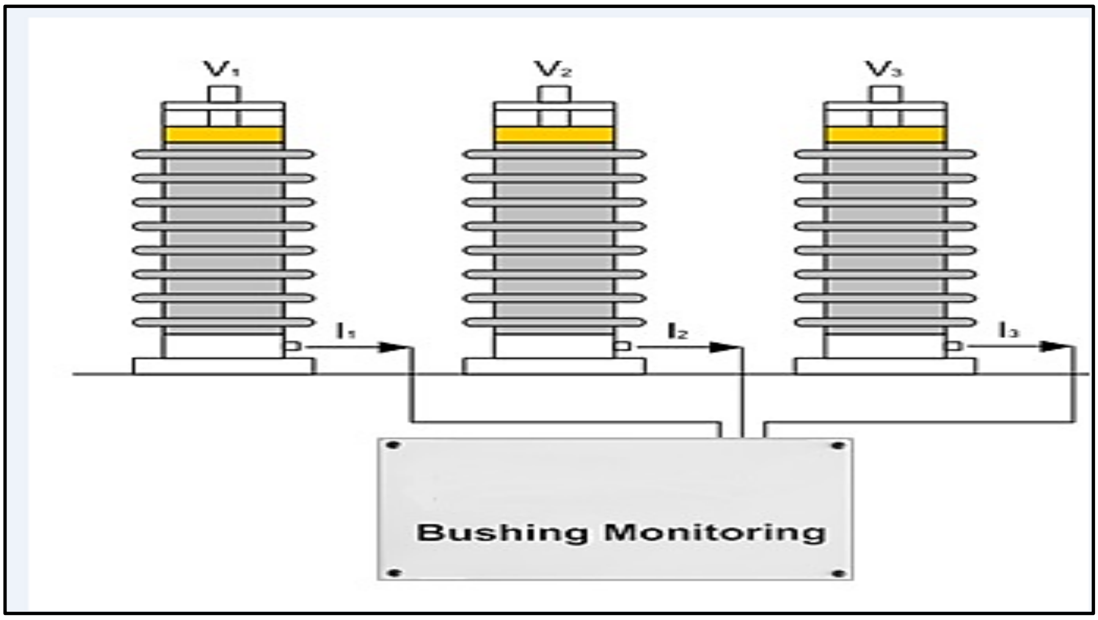


Figure 3.6: Bushing monitoring system illustration [40]

For best results, the bushing monitoring system offers a combination of analysis methods to provide fast and reliable determination of the actual bushing condition. For identifying changes in the bushing's condition, bushing power factor and capacitance values are commonly calculated by using the sum of three currents and adjacent phase analysis methods.

These analysis methods provide stable imbalance current and capacitance values, but in some cases the power factor data can be affected by temperature and power system voltage fluctuations, particularly on lower voltage bushings. If these conditions exist, the bushing monitor can be supplied with smoothing algorithms to eliminate any cyclical variation in the data, or the unsmoothed data can simply be evaluated for trends rather than instantaneous data points. Changes in bushing conditions can be easily detected with either approach.

The bushing monitoring system is designed to be permanently installed to monitor the condition of condenser bushings. To this end, up to six leakage currents are being measured online, but in this research the voltages, power factor and capacitance values will be monitored continuously.

3.3 Operating parameters monitored continuously

Power transformers are one of the most critical and expensive assets in the distribution business. They need to be efficiently operated and maintained throughout their life cycle to maximise design life and prevent failures. The research study will introduce the online condition monitoring for power transformers as one of the techniques to assess the condition of the power transformer during operation.

The online condition monitoring system is a unique technology that monitors the condition of various parameters of the power transformer. The data and remotely collected information from this system is used to determine the cooling state, ageing rate and transformer lifetime estimation. The collected information is also used to support maintenance planning by helping identify the relevant maintenance activities and interventions required on the power transformers [4].

In recent decade, a more sophisticated means has evolved for collecting a great deal of diagnostic information while the equipment is in service. This is known as continuous or online monitoring, which, when used expediently, can overcome some of the fundamental limitations of diagnostics that rely only on offline tests and other data. The monitoring of data is important and necessary to obtain complete diagnostic information on the condition of the transformer and its components [24].

Data monitoring, trending, and the associated diagnostic tools can be used to assist in developing new strategies or changing existing strategies such as those that dictate operational limits, maintenance programmes, additional testing or monitoring, and replacement decisions. Strategic enhancements can increase the performance and reliability of transformers, reduce maintenance costs, and aid in the optimisation of transformer operation and maintenance procedures [24].

Online monitoring cannot be used to predict end of life of transformers; however, it will assist to detect deteriorating conditions that can lead to premature transformer failure, so that timely replacement decisions before failure can be made.

3.3.1 Temperature monitoring

The load capability of power transformers is limited principally by the winding temperature. But the true limiting factor is the hottest winding section, since the winding temperature is not uniform over its extent. This section is called the winding hot spot, and it is located around the top of the winding. The hot spot temperature may be determined by a mathematical model with ambient temperature, top and bottom temperatures and the load current as inputs [25].

The isolation temperature is the main cause of transformer ageing. The cellulose isolation undergoes “depolymerisation” caused by temperature and time. As the cellulose chain becomes smaller, the mechanical properties of the paper, like traction resistance and elasticity are degraded. It's possible that the paper becomes fragile and is incapable to withstand the short circuit forces and the normal vibrations.

This points to the end of the life of the solid isolation, thus determining the end of transformer life. The hot spot monitoring allows taking advantage of cold ambient temperature to extend the transformer's lifetime, providing the capacity of urgent overload. Top oil temperature in a transformer is a very important parameter which can be used to determine the level of moisture in paper in your windings [25].

The three enemies of cellulose life are heat, water and oxygen. The worst of these is heat. Thus, if the transformer is run for long periods at high temperatures, the paper will degrade faster than when the transformer is running within normal temperatures. The high temperatures will damage the paper of the transformer, which will shorten the life of the unit. The load is increased until one of the following occurs:

- The relative ageing value over a 24-hour period reaches unity;
- The top oil or hot spot temperature reaches values of 105°C or 120°C respectively;
- The load level reaches 130%.

The top oil temperature, winding hot spot temperatures and the resultant loss of life are the ambient temperature and a typical 24-hour load profile. The ambient temperature in this case is fixed at the average maximum temperature for the region. Table 3.1 below contains representative values for specific regions.

Table 3.1: Average maximum ambient temperatures

Region	Temperature
Cape Town	26.5°C
George	24.6°C
East London	25.5°C
Johannesburg	25.6°C
Pretoria	28.6°C
Bloemfontein	30.8°C
Bethlehem	27.2°C
Kimberley	32.8°C
Durban	28.0°C
Port Elizabeth	25.4°C
Upington	34.3°C
Nelspruit	29.3°C
Polokwane	28.1°C

In this research study the online condition monitoring will monitor the following parameters for transformer operating temperature systems:

- Ambient temperature;
- Oil temperature indicator; and
- Winding temperature indicator

The temperature inputs PT100 sensors will be used in the active part of the transformer to measure all the recorded temperatures. The temperature data from PT100 sensors will be passed to a SITRAM condition monitoring cabinet via fibre optic cables to monitor the server in Kimberley for analysis and calculations. The sampling rates are configurable from weekly to hourly.

3.3.2 Load and ageing monitoring

Power transformers operating at full load, or near full load, transform a large amount of electric power that generates large amounts of heat. Power transformers require some type of cooling to mitigate the consequences of excessive heat. A fluid such as oil is used as a cooling medium to remove excess heat from the transformer core and windings. The transformer cores and windings are designed to permit the flow of the oil around and through all coils. This provides a method to remove heat generated internally. The oil is then typically circulated through air-cooled radiators. To increase radiator cooling capacity, fans may be used to increase air flow across the radiator [26].

There are two main sources of heating in power transformers:

- Current flow through the windings results in I^2R load losses. Increased current results in increased load losses, proportional to the load current squared; and
- Hysteresis and eddy current no-load losses due to core magnetisation. Increased applied voltage results in increased no-load losses, proportional to the applied voltage squared.

The heating increases the temperature of the windings and insulating oil. The maximum temperature occurs within the windings and is referred to as the hot spot temperature. The oil temperature within the tank is a maximum at the top of the tank, and is referred to as the top oil temperature [28].

The following risks are associated with transformer overload:

- Pressure build up as the top oil temperature increases beyond the design level, which leads to oil leakage and eventually failure if the transformer does not have a pressure release valve;

- Damage to the "accessories" such as the tap changer and bushings, which are not designed for operation beyond certain current levels (typically 150% of rated current);
- Paper degradation (paper is used to insulate each turn within the windings), due to continued operation at hot spot temperatures in excess of 98°C. Transformer paper life and hence transformer life is halved for every 6 degrees the transformer hot spot temperature exceeds 98°C; and
- As the insulation paper ages, its mechanical strength reduces. Failure occurs when the paper can no longer provide adequate insulation. This may occur following a through fault which mechanically stresses the windings, causing them to collapse, resulting in inter-turn faults.

Prior to beginning the overload calculation, the transformer tap position must be determined. Distribution transformers are designed to carry a maximum continuous current of 1.05 per unit (pu) and, if the voltage drops below 0.95 pu, then the transformer must be de-rated accordingly.

Example: If the incoming voltage is 0.9 pu then the new transformer rating is calculated as follows:

$$New\ rating = V \times I \times MVA_{rated} \qquad (3.\ 1)$$

Where,

V = voltage on primary side (pu)

I = maximum continuous current (pu)

MVArated = rated MVA on primary tap

$$New\ rating = 0.9 \times 1.05 \times MVA_{rated}$$

$$New\ rating = 0.95 \times MVA_{rated}$$

The transformer load must thus be limited to 95% of its rating on the principal tapping. The result is a temperature profile, which operates below the transformer rated temperature during off-peak conditions, and close to or above rated temperatures during peak conditions. IEC60354 provides guidelines for capitalising on periods of low load to allow the transformer to be "overloaded" during periods of high demand, without affecting the overall lifespan of the transformer insulation. Consider the following simple example of a 10 MVA transformer subjected to a residential load on a typical winter's day, as shown in Figure 3.7 below.

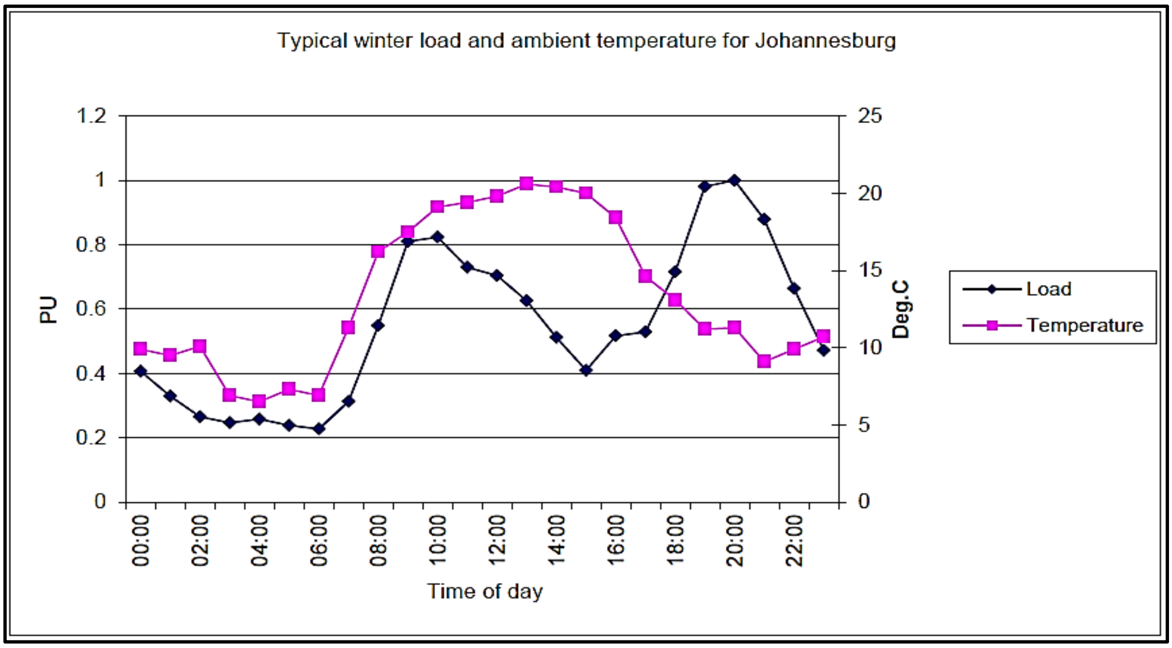


Figure 3.7: Load profile and ambient temperature [26]

The hot spot temperature, top oil temperature and cumulative loss of life for the above loading are shown in Figure 3.8 and Figure 3.9 respectively.

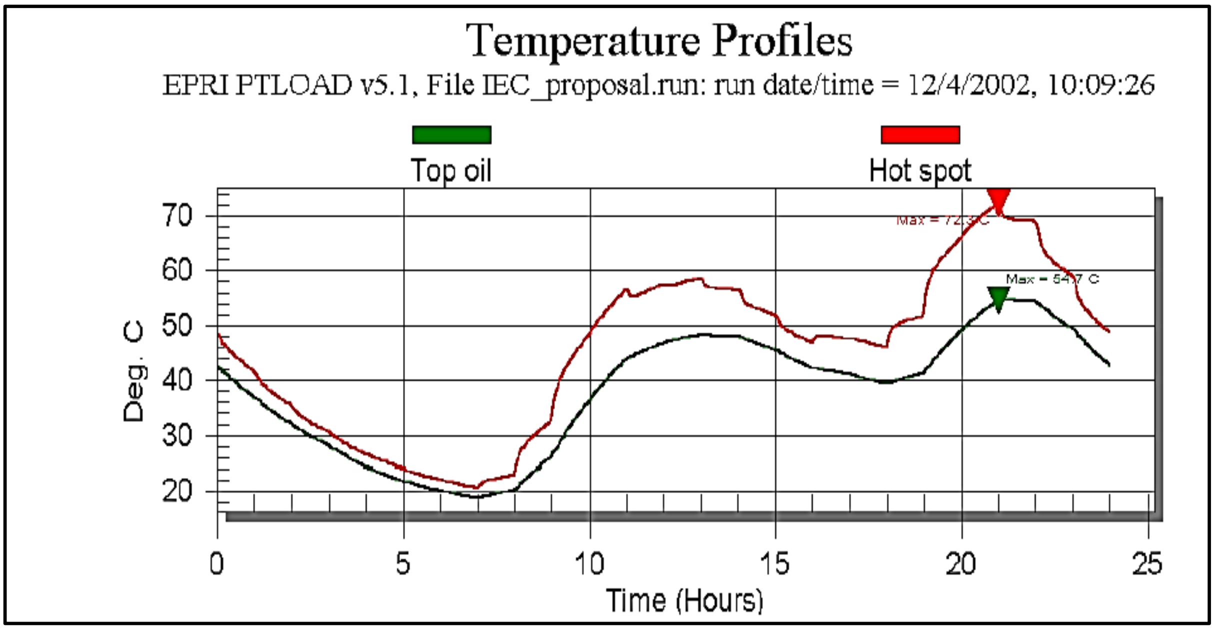


Figure 3.8: Top oil and winding temperatures [26]

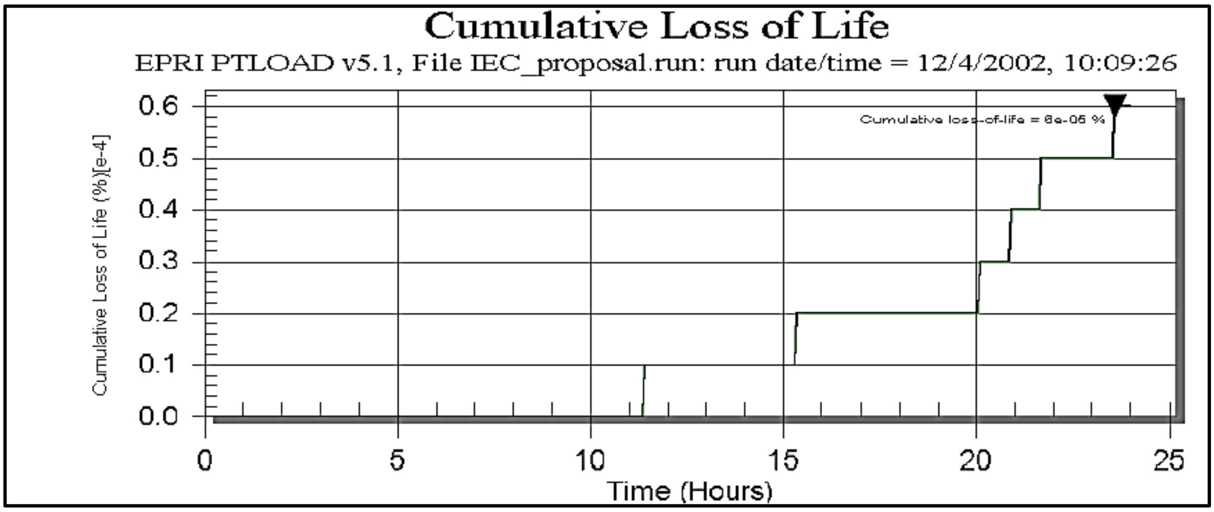


Figure 3.9: Cumulative loss of life [26]

Considering that the maximum allowable loss of life per day is 0.0079% (this results in a 35-year lifespan), one can see that this transformer is under loaded. Increasing the loading until the hot spot, top oil or loss of life limit is reached, a maximum loading of 146% is obtained. This means that the transformer could be loaded to a maximum of 146% of the nameplate rating, and the insulation would still last for 35 years.

The maximum loading is dependent on the load profile, ambient temperatures and target lifespan. Peaky loads result in increased loading limits, as the transformer oil and winding temperature time constants are such that the oil and winding temperatures lag the loading, and the steady state oil and winding temperatures are not reached (the load drops off before the steady state oil and winding temperatures are reached) [26].

The aging rate is determined by the winding hot spot temperature. Therefore, the first step in the analysis is to estimate the hot spot temperature. Sometimes this can be done directly via measured data using embedded fibre optic temperature probes (uncommon), or from a simulated winding temperature indicator. If the latter is the only measurement available, it may be advisable to calculate the temperatures using historical load, air temperature and (if available) oil temperature. In this research study the online condition monitoring will monitor transformer ageing and loss of life.

3.3.3 Moisture in oil measurement

Insulation material inside the transformer contains moisture. The main insulation materials in the transformer are cellulose paper, press board and transformer oil. There are moisture safety limits at which a transformer can operate on safely, both low and high. Over drying of the paper insulation causes shrinking, which results in winding loosening.

High moisture reduces the dielectric strength of the insulation. Abiding by the moisture limits will therefore reduce the risk of compromising the transformer. A paper sample would be required to measure moisture in paper, which can only be taken when a transformer is opened, normally on major repairs. That leaves only the prediction of moisture in paper by measuring the moisture in oil. Normally, an oil sample is taken once on a specific day, analysed and then moisture in oil is used to predict the moisture in paper. The instabilities of moisture in oil and paper in a power transformer are mainly due to temperature [27].

The most used moisture-in-oil sensors are based on thin film capacitive element technology. The capacitance measured changes roughly proportionally to the change in the relative saturation of moisture in the oil. The output of these devices is dependent on the temperature of the oil and the amount of moisture in the oil. If the temperature of the oil and the moisture solubility coefficients are known, the parts per million of moisture can be determined. Water in paper may be deduced from moisture in oil using equilibrium curves.

The most commonly used method for the estimation of water in paper is through the use of moisture in oil measurements and commonly available moisture "equilibrium curves" (also referred to as Piper curves or Oommen curves, named after the originators). As the name implies, this method relies on the assumption that the moisture in oil is in equilibrium with the water in paper [24].

An equilibrium chart is a graph that shows the relationship between oil temperature and the dissolved water in oil. Figure 3.10 shows a typical Equilibrium chart, which at first glance, is rather a complex graph with many hidden problems. The original curves have been modified to include the insulation moisture limits for different voltage classes of transformers. Given the average oil temperature of the transformer and the measured moisture content of the oil, the moisture content of the cellulose can be estimated from the chart in Figure 3.10 below. It can also be determined if the moisture content is excessive and action is required.

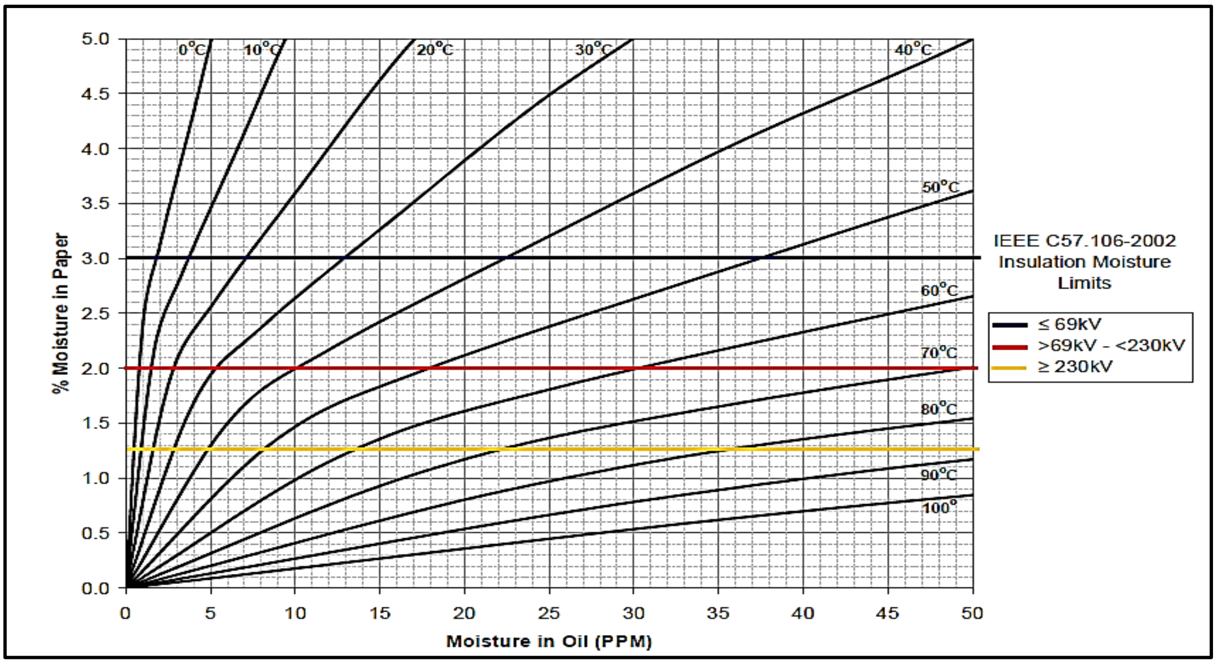


Figure 3.10: Modified Oommen curves for moisture equilibrium chat [25]

In this research study the online condition monitoring will monitor the following parameters for moisture in oil:

- Gas pressure of air in oil;
- Oil moisture (relative saturation);
- Temperature of bubble formation;
- Average moisture content in cellulose;
- Average Cellulose Moisture in bottom conductors wrapped insulation;
- Average Cellulose Moisture in bottom cold insulation;
- Average Cellulose Moisture in top cold insulation;
- Average Cellulose Moisture in top conductors wrapped insulation;
- Average Cellulose Moisture in top conductors wrapped insulation (surf); and
- Oil moisture.

3.3.4 Tap changer monitoring

The use of online tap changer monitors has been successful in reducing maintenance costs. The data from these monitors are used to determine when mechanical problems with the mechanism are occurring, and when contacts should be examined or changed, rather than through periodic inspections. The systems monitor motor current, torque and run time, and differential temperature between the main and tap changer conservator tanks. The basic principle is that contacts that are nearing the end of their life or that are coking generate additional heat, which raises the temperature of the oil in the compartment.

When carbon is extracted from the surrounding oil and is deposited on a contact, it is said that a coking process is taking place. The coking process is a chemical reaction where pyrolitic carbon is created [28]. In general, this happens when the contact is extremely hot, so that the activation energy is available to start the chemical reactions which the coking consists of. The process is initiated by the formation of a thin oil film on the contact [28].

The oil film, which consists of polymerised oil, reduces the conduction of the contact spot, thus leading to higher resistance. The higher resistance will in turn generate more heat, which induces the formation of a thicker oil film layer.

The tap changer diverter compartment usually runs cooler than the main tank, and the selector compartment runs cooler than the diverter switch compartment. Since the On-load Tap Changer (OLTC) Tank is thermally coupled to the Main Tank, abnormal heating within the OLTC can be observed by monitoring this temperature difference. If the temperature of the diverter switch compartment starts to increase in comparison to the main tank or the selector compartment, there is usually a contact problem [24].

If the selector and the diverter are in the same compartment, the temperature of the tap changer compartment must be compared to the main tank. The online monitors use temperature sensors located on the walls of the tap changer compartments and the main tank. The output is connected to recording and analysis equipment. Alarms can be activated if the temperature of the diverter compartment reaches a level indicating that the contacts should be inspected or changed. There are however some important factors that must be considered when employing the technique of differential temperature monitoring. If the sensors are surface mounted they may not be immune to heating caused by sunlight.

The monitoring system must have the ability to differentiate between actual abnormal heating problems in the OLTC versus heating caused by sunlight. Since the OLTC Tank is a much smaller volume of oil, it heats up more quickly than the Main Tank on a cool but sunny day. False positives are likely if the differential detection system does not have the ability to differentiate between sunlight heating and abnormal OLTC heating [25].

In this research study the online condition monitoring will monitor the following parameters for OLTC:

- Phase-to-ground voltage; and
- TAP position.

3.3.5 Bushing monitoring

The online monitoring systems are available for monitoring the insulation quality of transformer mounted bushings by continuously monitoring the leakage current, insulation power factor and capacitance. The online monitoring of the power factor, capacitance and leakage current is a better method of providing a definitive clue to the integrity and health of the insulation than performing the same measurements offline.

For example, offline measurements of power factor are usually performed on a moderate day with low humidity and at a relatively low voltage (10 kV). The bushing however, is operating under all types of environmental and loading conditions and at operating voltage.

These conditions impact the bushing's power factor. Thus, online monitoring systems provide the earliest indication of the condition of the insulation integrity of the bushing, since they have the advantage of operating continuously and acquiring data under all weather and environmental conditions. This also includes leakage due to surface contamination due to pollution and salt spray. A bushing can be represented by several small capacitance values in series and parallel, as shown in Figure 3.11.

As a fault occurs in the bushing, the insulation in some of these very small capacitors cracks and becomes more resistive, as indicated in the Figure 3.11 by the single capacitor with the line struck through it. The leakage current from deep inside the bushing is miniscule and is difficult to measure in the ground connection. However, by utilising a capacitive voltage divider, the voltage drops due to a change in the value of these capacitive/resistive components can be sensed and measured by the bushing monitor connected to the bushing capacitance tap [24].

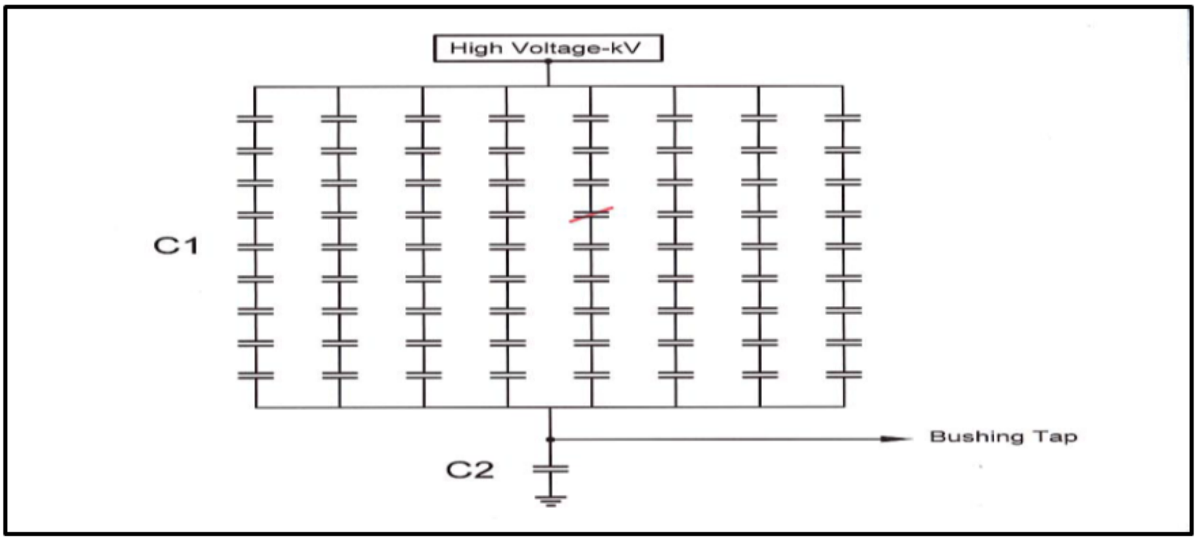


Figure 3.11: Schematic representation of a bushing [24]

One method of analysing the health of these capacitors is by use of the Relative Power Factor technique. This technique uses the concept of a "Virtual Schering Bridge." The power factor of a bushing as a relative value is determined by comparing the bushing tap voltage with a reference voltage from another device that is in service. This eliminates the need for a precision standard capacitor as is used in the standard Schering Bridge circuit, as shown in Figure 3.11[24].

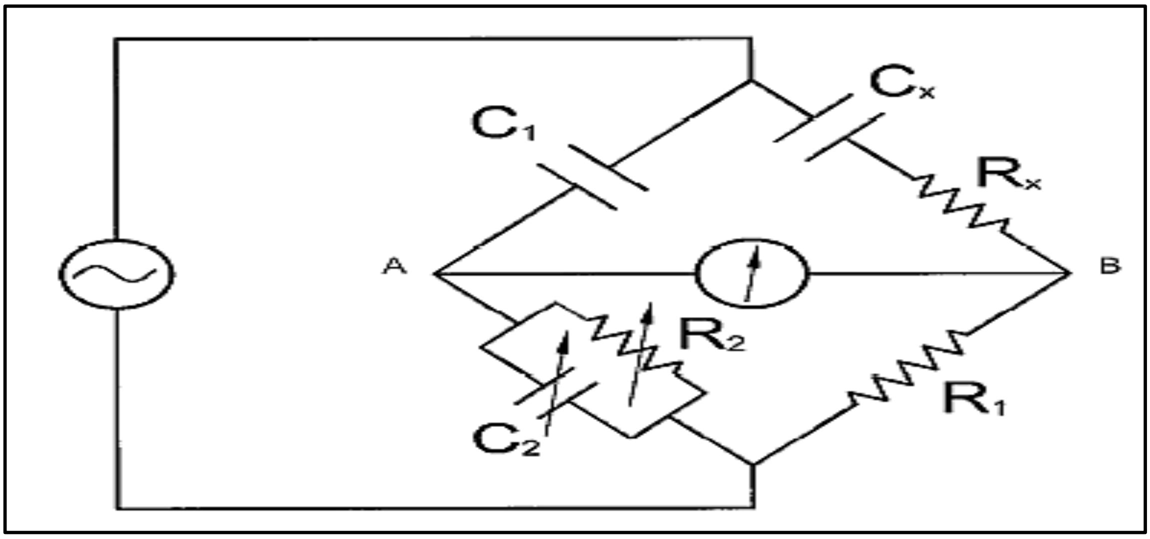


Figure 3.12: Standard Schering Bridge Circuit [26]

The components of the standard Schering Bridge are:

C_1, a standard capacitor of known capacitance of high precision and stability

R_1, a standard resistor of known resistance of high precision and stability

R_2 and C_2, variable components used for balancing the bridge

C_X and R_X, the unknown capacitor to be measured

When the bridge is balanced, i.e. when points A and B are at the same potential, $C_1/Z_2 = Z_X/R_1$, where Z_2 is the impedance of R_2 in parallel with C_2, and Z_X is the impedance of C_X in series with R_X. From this, the capacitance and power factor of the capacitance under test can be calculated.

In the Virtual Schering Bridge, the same bridge concept is used except that a voltage reference is taken from a bushing that simulates the reference capacitor. The reference device does not have to be associated with the same phase, since the virtual Schering Bridge (software algorithm) will automatically make the proper phase angle adjustments. Relative measurements and evaluation can reduce the effect of influences such as ambient temperature, operating voltages, loading conditions, different aging characteristics, different designs, operating conditions, etc. The power factor or Tan δ calculation is based on the fundamental Schering Bridge calculation. Data is acquired under software control from the bushing sensor represented as C_X in series with R_X in Figure 3.12. The data is compared to data from another bushing used as a reference shown as C_1. The amount of difference between the two measurements is calculated as the relative change in power factor and capacitance between the two bushings under test.

One of the advantages of this technique is that each bushing can be compared to all other bushings in the substation, which removes any ambiguity with regard to which bushing is changing when only two bushings are compared. The software permits entering the power factor value of the last offline test (preferred) or nameplate power factor values for each bushing monitored. Using this value, the power factor can be normalised to give an actual power factor (rather than a relative power factor) which is comparable to an offline test value. Figure 3.13 is a photograph of a power factor sensor connected to the bushing capacitance tap.

Figure 3.13 Sensor installed on an HV bushing test tap

The critical values that a bushing monitoring system provides are:

- Test tap -voltage which can be used to monitor the power system operating voltage;
- Relative power factor - calculated in relation to each bushing monitored;
- Power factor – measured on each bushing monitored;
- Condition value - the result of a statistical analysis technique which indicates the condition of the bushing; and

- Sum current – requires measurement from three bushings and can provide information on which bushing is deteriorating.

The monitoring system should be installed on or near the transformer to keep installation costs at a minimum. The manufacturer of the equipment should provide the equipment in a rugged enclosure that meets National Environmental Management Act (NEMA) or Ingression Protection standards for an outdoor electronic enclosure.

All cabling and sensors should be run in conduit and protected from the outdoor environment. The equipment should have remote accessibility through the substation network and/or SCADA. The equipment should be accessible to monitor alarms and for communication with the unit to check on the monitored equipment status during time of alarm or for periodic data collection and review.

3.3.6 Dissolved gas analysis monitoring

One of the most useful and most widely used condition assessment techniques involves sampling and analysis of gases dissolved in the oil of operating transformers. This technique is sensitive to a wide range of malfunctions, both thermal and electrical, which could eventually lead to failure of a transformer if corrective measures are not taken.

For offline testing, sampling intervals are typically 6 months to 3 years, depending on the size and voltage of the transformer; with more frequent sampling for large, critical units and less frequent sampling for smaller, less critical units. With online testing, samples are taken and analysed in time intervals of hours or even less. Overstressed insulation (electrical and thermal stressors) and overheated metallic parts in oil-filled transformers produce various gases which are absorbed into the oil. The quantity and composition of these gases depend partly on the kind of insulation and the temperature.

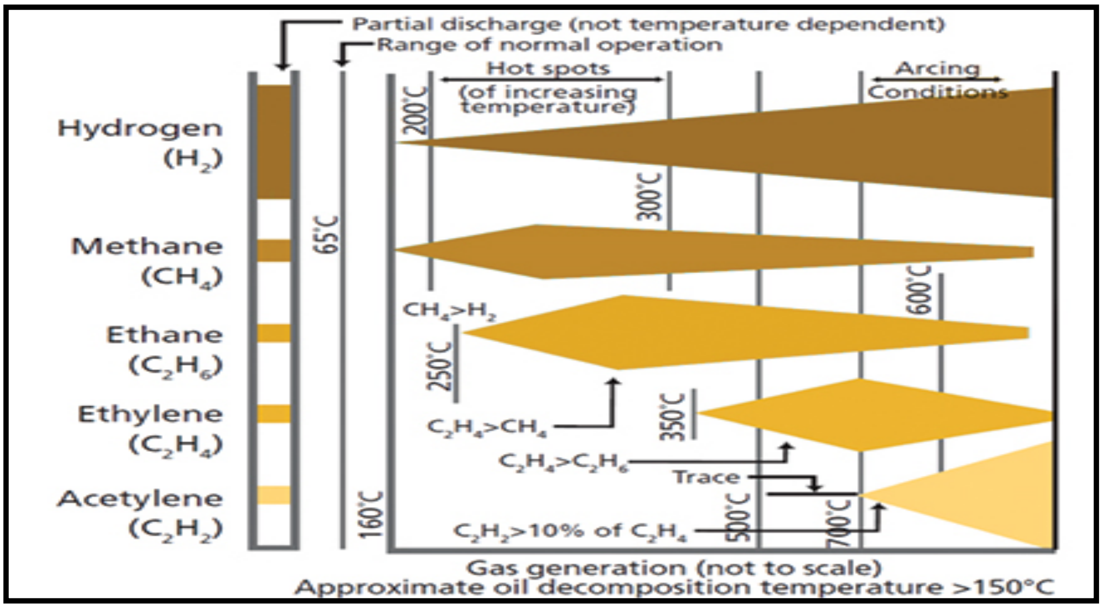


Figure 3.14: Gas generation chart [29]

Figure 3.14 illustrates schematically and qualitatively the relative generation of the various gases versus oil temperature, and Table 3.2 shows the most important gases used in diagnostics and the temperature at which significant generation occurs. These are only qualitative; in practice, mixtures of all these gases, particularly the first four, are always observed, and gas compositions are more complex than depicted in Figure 3.14 and Table 3.2.

By extracting the gases from the oil and analysing them, it is possible to diagnose the kind of failure which produced them and in some cases where the damage is occurring. DGA is the procedure by which the gases are analysed. The type of gases and their concentration in the oil are used to identify problems in a transformer before a failure occurs.

Some examples of defects which produce different gases are:

- Overheating of oil, or of winding conductor paper covering, or of joint tape;
- High temperature hot spots in the core, or at defective welds or contacts;
- Sparking in oil or in paper insulation;
- Tracking on pressboard insulation;
- Flashovers in oil to the ground or tank walls; and
- Short circuits in windings or core

The test procedure is to take a sample of oil, have it analysed by the laboratory or the online monitor, examine the gas composition, and use the various diagnostic techniques to compare the gas mixtures with published data. Attention has to be paid to the type and family of transformer examined, to the history of the transformer and its condition of operation.

Table 3.2: Fault gases versus generation temperature

Gas	Temperature of significant generation
Hydrogen (H_2)	<150°C with ionization (PD) >250°C
Methane (CH_4)	150-200°C
Ethane (C_2H_6)	200-400°C
Ethylene (C_2H_4)	300-700°C
Acetylene (C_2H_2)	>700°C

It is of utmost importance that results should be interpreted only by an experienced person. Gas levels in particular should be taken into account to determine how serious a fault may be. Gas formation trends are important for proper diagnosis and are usually essential indicators.

One should not base a million-dollar decision on a single sample, or make a diagnosis based on dissolved gases as an indisputable fact [30].

IEEE C57.104 and IEC 60599 are invaluable aids for interpretation of gas in oil analysis results. The IEEE Guide offers advice on both a simple qualitative interpretation based on certain “key gases,” as well as a more detailed quantitative diagnosis based on absolute levels and ratios of gases. In addition, it provides a rational step-by-step action plan to carry the user from the first recognition of abnormal gas generation and trending, through an increased surveillance period, to possible removal from service [30].

Note that different results may be expected from lab analyses compared with online DGA. Trends are much more easily recognised with online gas monitoring and gas in oil concentration changes due to the absorption and desorption of certain gases into and out of the cellulose insulation, which makes correct interpretation from periodic testing difficult [31].

In this research study the online condition monitoring will monitor the following DGA parameters of a power transformer:

- Gas in oil content (Up to 9 gases);
- Gas in oil rate of change;
- Relative moisture in oil%; and
- Water content in oil.

3.3.7 Cooling system monitoring

Many transformer monitoring and control systems can monitor motor load current via split-core current transformers, and provide both a timed over-current and a timed under-current that allow detection of motor failure or binding. These set points provide a “sweet spot” for motor current.

In this research study the online condition monitoring will monitor the following cooling parameters of a power transformer:

- Current in amps for the fan; and
- Motor run time in hour, and estimating the remaining life of the motor.

3.4 System sizing and costs

System component costs consist of capital, replacement, operation and maintenance (O&M) costs. The system sizing and costs answers the question: “What is the cost of online monitoring, and is it worth the resource investment?” A successful business case is not complete without a thorough analysis of the costs and benefits associated with implementing the proposed online monitoring solution for this research study.

Online monitoring solutions do not get installed overnight, as such projects involve numerous departments and organisations. The timeline section provides the decision makers with the assurance that their team has carefully and professionally considered all major factors related to the implementation. A number of major elements that are important for the successful implementation of online monitoring, and that should be addressed include:

- Implementation components;
- Design and specification;

- Procurement;
- Installation;
- Integration;
- Training;
- Operation and response;
- Maintenance;
- Installation timeline;
- Major milestones; and
- Dependencies.

The online monitoring is generally one of several potential solutions being considered. The other solutions should be briefly covered, including a concise list of their merits and deficiencies. Finally, the strengths, weaknesses, opportunities and risks that are associated with the recommended solution are to be described along with a discussion of the impacts associated with not implementing the solution.

The aim is to gauge the efficiency and effectiveness of the online monitoring investment and resulting changes in maintenance and operating practices relative to the status quo. The benefits of the online monitoring were previously discussed and are evaluated in terms of expected improvements in operations, process efficiencies, reliability, availability, asset life or new services. Inputs are typically measured in terms of opportunity costs, whilst outputs are measured in terms of cost reductions, avoided expenses, improved service, life extension or risk reduction. In this research study the real costs will be used to determine whether the utility will save or will lose money when purchasing the online condition monitoring technology in the research site.

The aim is to reduce maintenance and monitoring costs based on:

- Transformer monthly routine visual inspections;
- Transformer time-based maintenance (test, maintain and calibrate);
- Transformer DGA, dielectric and water routine oil sampling;
- Transformer age assessment oil sampling;
- Tap changer time-based maintenance;
- Transformer offline moisture removal; and
- Transformer replacement costs (including transportation);

Costing calculated on skilled labour travelling (Northern Cape Province long distances) to complete routine inspections and maintenance as per task manual is 200 km on overage.

Direct costs include:

- Labour;
- Transport;
- Travel and subsistence;
- Material; and
- 6% inflation.

Table 3.3: Summary of maintenance tasks and costs for power transformers

Year	1	2	3	4	5	6	7	8	9	10	Total
Visual inspections	R 17 265	R18 300	R19 398	R20 562	R21 796	R23 104	R24 490	R25 959	R27 517	R29 168	R227 559
Maintenance						R 42 377					R 42 377
Oil sampling (main tank)	R 6 755	R7 160	R7 590	R8 045	R8 528	R9 040	R9 582	R10 157	R10 766	R11 412	R89 035
Oil sampling (Tap changer)			R7 590			R9 040			R10 766		R27 396
Oil sampling (Age assessment)					R3939					R5 271	R9 210
Offline moisture removal						R20 000					R20 000
Strategic spares costs								R 11 079 419			R 11 079 419
Strategic spares transportation								R1 200 000			R1 200 000

Table 3.4: Total cost for maintenance/monitoring and asset replacement over ten years

Maintenance task	Amount (R)
Visual inspections	R227 559
Transformer maintenance	R 42 377
Oil sampling (main tank)	R89 035
Oil sampling (tap changer)	R27 396
Oil sampling (age assessment)	R9 210
Offline moisture removal	R20 000
Strategic spares costs	R 11 079 419
Strategic spares transportation	R1 200 000
Total	R 12 694 996

Since R12 694 996 is a maintenance/monitoring and asset replacement expenditure for a ten year period, it means the expenditure would be R1 269 499 per year, whereas the cost for installing transformer online condition monitoring system amounts to R1 296 910 once off. Installing such an online monitoring system will therefore bring about a total saving of R11 398 086 over a period of ten years as compared to the current costs of maintenance/monitoring and asset replacement strategies. The total saving would be R1 139 809 per year for tasks such as inspections/maintenance/monitoring and asset replacement.

CHAPTER 4: **ONLINE CONDITION MONITORING RESULTS AND DISCUSSION**

4.1 Online condition monitoring results and discussion

This chapter discusses the online condition monitoring results in detail. In this research no modelling or simulating study methods will be used, since the data will be retrieved directly from the online condition monitoring server. The results will then be discussed and analysed from the data retrieved in the server. This chapter discusses the results of each transformer parameter monitored by online condition monitoring technology installed in the research site.

International standards such as the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) will be used as a guideline to discuss the online condition monitoring results. Other Dissolved Gas Analysis (DGA) methods to be discussed in this research study is IEC Duval, IEEE Key Gas, IEEE Ratio methods; IEEE Doernenburg and Electric Technology Research Association (ETRA). However, DGA techniques such as Duval triangle, ETRA and ratio methods (Doernenburg, Rogers and IEC) could not be used, as gas concentration levels are too low.

The DGA diagnostic method will be used in this research study to predict the faults in power transformers on the research site. The results from the bushings, cooling fans, tap changer and temperatures will also be discussed in this chapter. The online condition monitoring technology is installed on the new 80MVA’s 132/66/22kV, transformer number 1 and transformer number 3 at Kimberley Distribution Substation (KDS) in the Northern Cape Province. Refer to Table 4.1 below for the name plate information of both transformers.

Table 4.1 Transformers number 1 & 3 name plate information

Transformer bay	Transformer 1	Transformer 3
Serial number	31060	W1262087
Substation	KDS	KDS
Power rating	80 MVA	80 MVA
High voltage rating	132kV	132kV
Medium voltage rating	66kV	66kV
Low voltage rating	22kV	22kV
Oil volume	33509 litres	33509 litres
Oil brand and type	Engen power 60U	Engen power 60U
Cooling type	Oil natural air forced	Oil natural air forced
Year of manufacture	2010	2012
Active part configuration	Core Type	Core Type
IEC 60599: 2007 category	B	B
Bushings type	Resin impregnated paper	Resin impregnated paper
Tap changer type	On-load	On-load

4.2 Problems with data collection

Since this technology (software and hardware) was implemented for the first time, several challenges were experienced during data collection in this research project for both server and sensors. One of the challenges experienced pertains to the online condition monitoring system server, where the event log was overloaded with data. When the database is overloaded with events, the historical data for trending purposes cannot be retrieved. The cause of this was the relatively large fluctuations in voltage on the transformer's High Voltage (HV) side. The system generated around 25 000 events in the database over the course of six months (approximately 4 170 events per month). To overcome this problem the database had to be cleaned up, and the HV warning and alarm values had to be adjusted in an attempt to combat the instability present on the HV supply to the transformers, to prevent this problem from reoccurring in the future.

The other difficulty experienced during data retrieval was the timestamp. Each sensor collecting data has its own separate timestamp. The data from the sensors are not retrieved at a fixed time interval (i.e. 10 minutes, hourly etc.). Each sensor will send the value when there is a change in the parameter. As a result, each sensor will send data at a different timestamp, which makes it difficult to correlate data because of the different timestamps.

4.3 Online condition monitoring results and discussion

The results from dissolved gas analysis, bushings, cooling fans, tap changer and temperatures will be discussed in detail in this chapter.

4.3.1 Dissolved Gas Analysis (DGA) condition monitoring results discussion

For many years the method of analysing gases dissolved in the oil has been used as a tool in transformer diagnostics. The method has been used for several purposes: to detect incipient faults; to supervise suspect transformers; to test a hypothesis or explanation for the probable cause of failures or disturbances which have already occurred; and to ensure that new transformers are healthy. Dissolved Gas Analysis (DGA) could also be used as part of a scoring system in a strategic ranking of a transformer population [12]. What is said about DGA for transformers is also applicable to reactors, instrument transformers and bushings. It is worth noting that DGA is a fairly mature technique employed by several companies around the world either in their own plants, or in co-operation with affiliated or independent laboratories. In assessing dissolved gases in oil, the rate of increase of different gases during a time interval is the most important indicator of the health of the unit. The actual gas levels may not be of consequence for the operation or the health of the transformer [12].

The online condition monitoring systems deliver a valuable contribution for early detection of malfunctions, for general gathering of condition information, and for diagnosis in power transformers. The DGA data from the online condition monitoring system could have assisted an engineer to make a decision to remove the transformer shown in Figure 4.1 below in service before the failure could happen.

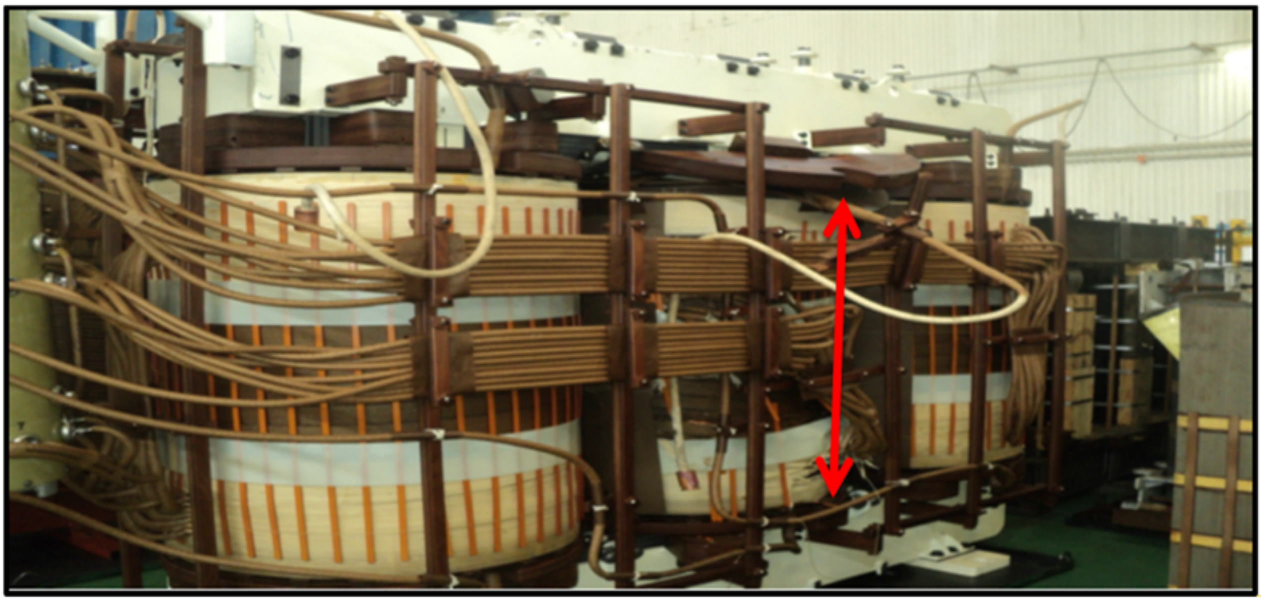


Figure 4.1: Active part of failed transformer

In Figure 4.1 above (where the red arrows are pointing) it can be seen that the windings on the blue phase limb of the transformer had failed. As a result, the top-yoke and pressure rings were damaged by the axial forces which had been produced by the windings during the fault period. It was also found that carbon and molten copper particles were produced during the fault period, which contaminated the windings and remaining insulation of the transformer. The DGA data from the online condition monitoring system could have assisted to detect incipient faults before the failure occurred.

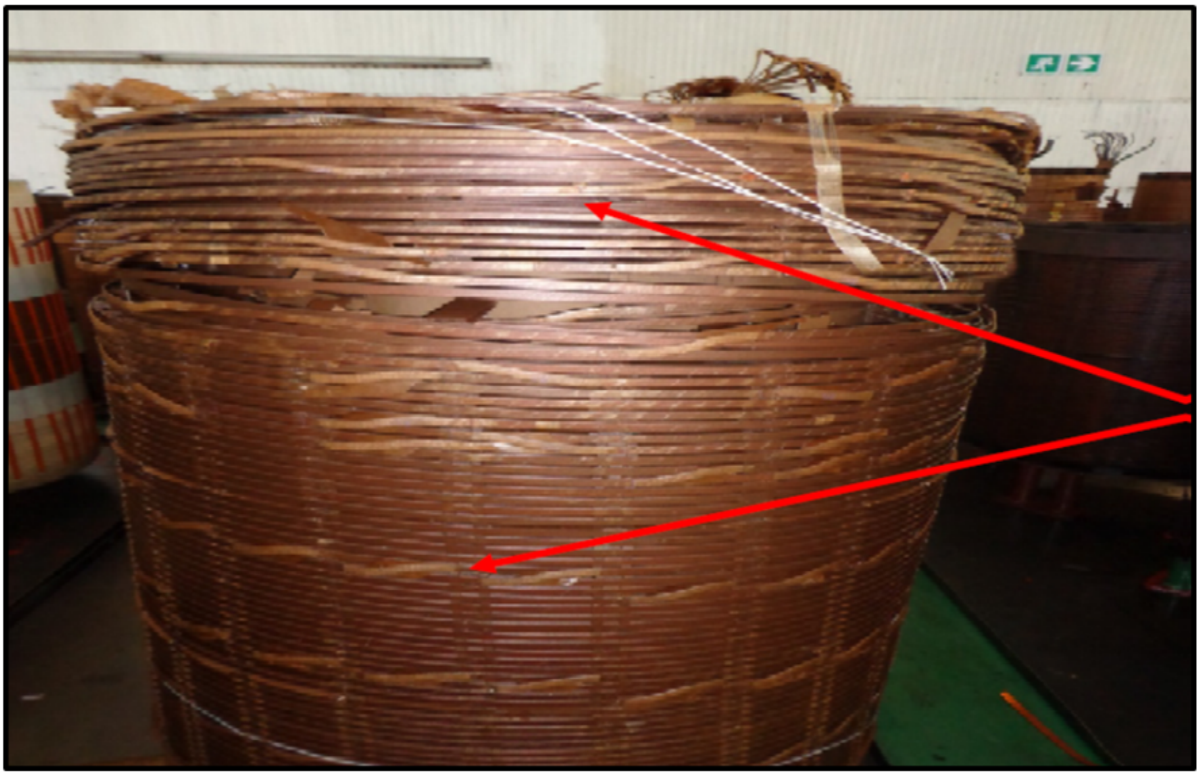


Figure 4.2: Damaged occurred in the blue phase high-voltage winding of transformer

The Figure 4.2 above shows the extent of the damage which occurred on the blue phase of the high-voltage winding of the transformer. Excessive movement occurred on the top section of the winding, and the bottom section of the winding was severely distorted, as indicated by the red arrows.

The DGA data from the online condition monitoring system could have assisted an engineer to make a decision to remove the transformer in service before that failure shown in Figure 4.2 could occur. The idea behind the use of dissolved gas analysis is based on the fact that during its lifetime, all oil/cellulose-insulated systems generate decomposition gases under the influence of various stresses - both normal and abnormal. The gases that are of interest for the DGA analysis are shown in Table 4.2.

Table 4.2: Dissolved and total dissolved combustible gases

Gas	**Symbol**	**Comments**
Hydrogen	H_2	
Methane	CH_4	
Ethylene	C_2H_4	
Ethane	C_2H_6	
Acetylene	C_2H_2	
Carbon monoxide	CO	
Carbon dioxide	CO_2	
Oxygen	O_2	
Nitrogen	N_2	
Total dissolved combustible gases	TDCG	$(=H_2+CH_4+C_2H_4+C_2H_6+C_2H_2+CO)$

There are several established techniques for the analysis of dissolved gases in transformer oil. These include, amongst others, the IEEE Ratio Method, IEEE Key Gas Method, ETRA, Duval's Triangle, and Doernenburg's Ratio Method, etc. Some methods rely on the parts per million (ppm) of the different gases (TDCG) in oil for interpretation, while others preferred to look at the ratio of the various gases to each other.

TDCG is used to detect the possibility of a fault, and is formed by adding the concentrations of H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and CO to find the total concentration in ppm [32] [33]. IEEE Std C57.104 defines four conditions as illustrated in Table 4.3.

Table 4.3: TDCG conditions

Conditions	**TDCG levels (ppm)**	**Interpretation**
Condition 1	<720	Transformer is operating satisfactory
Condition 2	721 to 1920	Transformer exceeds normal values, additional investigation is required, key gases should be checked for a fault
Condition 3	1921 to 4630	High level of decomposition, additional investigation is required, key gases should be checked for a fault
Condition 4	>4630	Excessive decomposition. Continued operation could result in failure

A key gas method is used to identify the type of fault, as there is a dominant or key gas produced depending on the temperature and type of fault [32] [33]. The key gases are summarised below [32] [33]:

- Thermal – Oil – C_2H_4
- Thermal – Cellulose – CO
- Electrical – Partial Discharge – H_2
- Electrical – Arcing – C_2H_2

Ratio methods relate the ratios of gases to the type of fault. Considering the following ratios [35]:

- Ratio 1 CH_4/H_2
- Ratio 2 C_2H_2/C_2H_4
- Ratio 3 C_2H_2/CH_4
- Ratio 4 C_2H_6/C_2H_2

- Ratio 5 C_2H_4/ C_2H_6
- Ratio 6 C2H6/CH4

The Doernenburg Ratio uses ratios 1, 2, 3 and 4, while the Rogers ratio uses 1, 2, 5 and 6 to interpret the type of fault occurring [32] [33].The IEC defines a Basic Gas Ratio Method as shown in Table 4.4, which gives the fault conditions shown in Table 4.5 [32] [33].

Table 4.4: Gas ratio codes for basic gas ratio

Gas ratio	**Range**	**Code**
C_2H_2 /C_2H_4	<0.1	0
	<3 and >0.1	1
	>3	2
CH_4 /H_2	<0.1	0
	<1 and >0.1	1
	>1	2
C_2H_4 /C_2H_6	<1	0
	>1 and <3	1
	>3	2

Table 4.5: Fault classification

Fault Type		**C2H2 /C2H4**	**CH4 / H2**	**C2H4 / C2H6**
Normal aging, no fault		0	0	0
Partial discharge (low energy)		Insignificant	1	0
Partial discharge (high energy)	PD	1	1	0
Discharges of low energy	D1	1 or 2	0	1 or 2
Discharges of low energy	D2	1	0	2

Thermal fault of <150 °C		0	0	1
Thermal fault of > 150 °C and < 300 °C	T1	0	2	0
Thermal fault of > 300 °C and < 700 °C	T2	0	2	1
Thermal fault of > 700 °C	T3	0	2	2

Michel Duval of Hydro Quebec developed the Duval Triangle in the 1970s. It was developed by analysing DGA databases and relating the DGA to the root cause analysis. The Duval's triangle was first used in IEC 60599, and has since proven to be a reliable method for the identification of the type of faults on transformers with a known problem [35].

Duval Triangle uses three gas ratios in a triangle, as shown in Figure 4.3, with the fault conditions listed in Table 4.6. The more recent Duval Pentagon uses five gas ratios in a pentagon as a tool to interpret the dissolved gas [35]. As Duval's Triangle does not have a normal condition, it should not be used for fault type prediction [36].

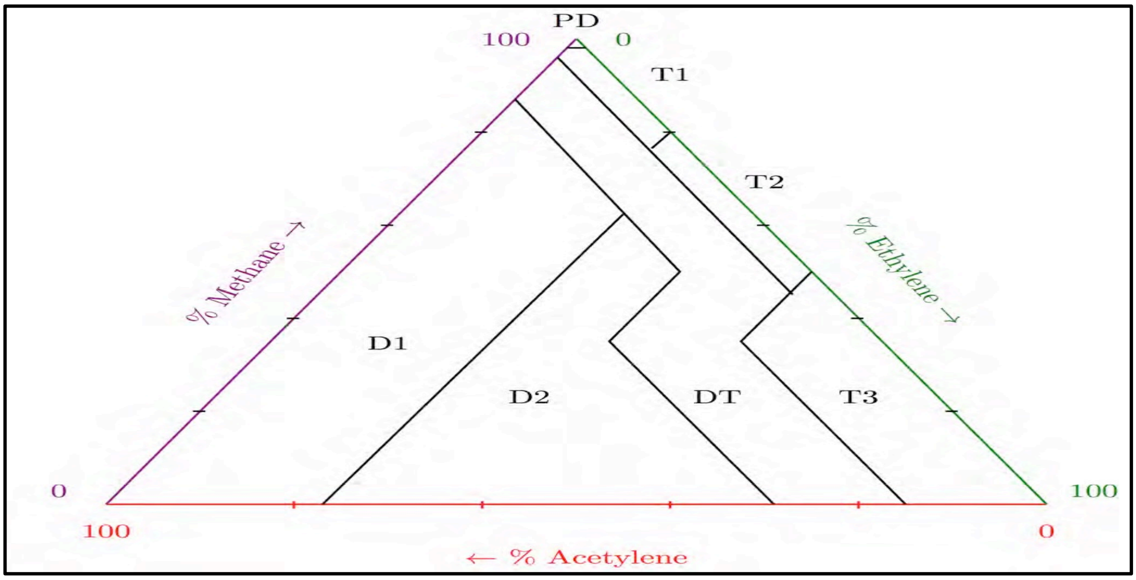


Figure 4.3: Revised Duval's Triangle [36]

Table 4.6: Duval's Triangle [36]

Fault code	Fault type
PD	Partial discharge
D1	Low energy discharge
D2	High energy discharge
DT	Mixture of electrical and thermal faults
T1	Thermal faults T < 300 °C
T2	Thermal faults 300 °C < T < 700 °C
T3	Thermal faults T> 700 °C

For the transformer operator it is important that the oil sample data are not looked at in isolation. It is best used in conjunction with operational information and in comparison to the baseline of normal operation of the transformer [37].

Trending of oil sample data is essential in establishing clear baselines that will easily highlight deviations from the normal condition. It is also advisable to use multiple methods of oil analysis to diagnose faults, as different methods have complementing strengths and weaknesses. For example, methods that focus mainly on ppm values tend to struggle with the early detection of faults due to their reliance on ppm thresholds for analysis.

Methods that rely solely on ratios may provide false indications, as even minor changes in the composition of gases may create unfavourable ratios. Methods such as the Duval Triangle and Key Gas Method do not have a normal condition, and are thus best used for root cause analysis once it is known that a fault exists [38].

4.3.1.1 Transformer number 1 DGA results and discussion at research site KDS

The results and DGA trends of transformer 1 at KDS are plotted on Figure 4.4 below. Transformers 1 and 3 to be monitored for this research study are both fitted with gas analysers.

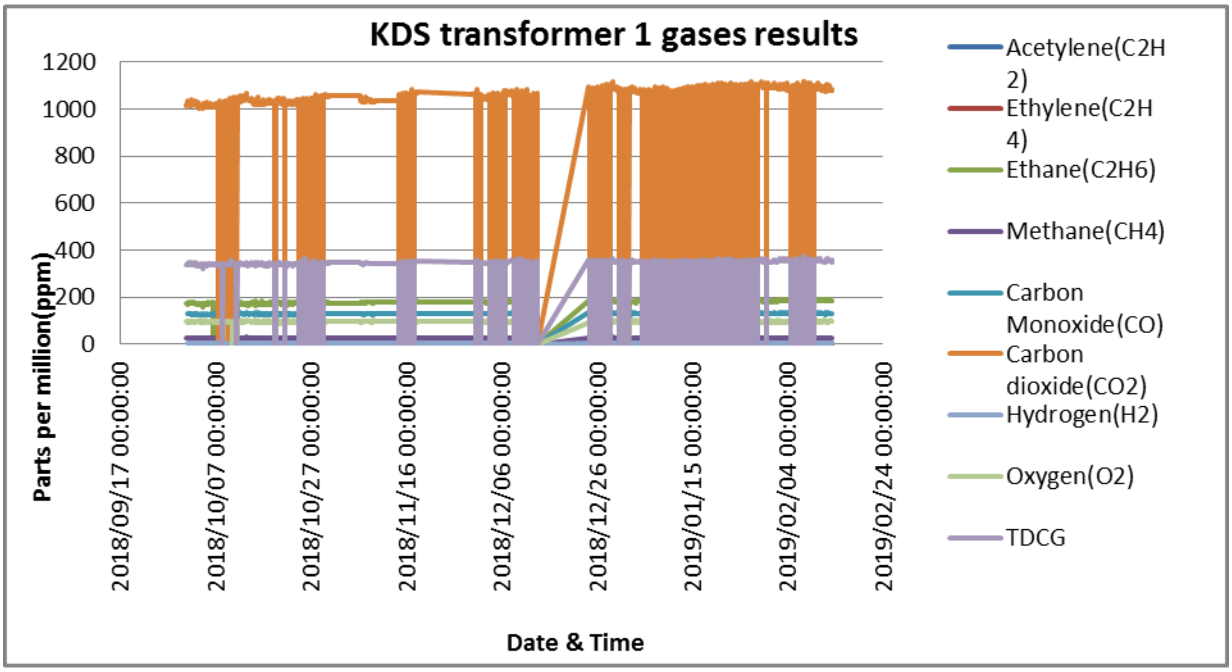


Figure 4.4: KDS Transformer number 1 gases trend

Figure 4.4 above shows the results of eight gases (namely Acetylene as C_2H_2, Ethylene as C_2H_4, Ethane as C_2H_6, Methane as CH_4, Carbon Monoxide as CO, Carbon Dioxide as CO_2, Hydrogen as H_2, Oxygen as O_2 and TDCG) monitored by transformer online condition monitoring at KDS in this research study. It is important to indicate that N_2 gas is not included on the graph shown in Figure 4.4. The reason for exclusion is that under normal circumstances N_2 gas is always present in the atmosphere, and its level is normally high. If the N_2 gas result was to be included in the graph, it would disarrange the scale and trend.

Transformer number 1 dissolved gas analysis results as shown in Figure 4.4 above indicate abnormal Ethane (C_2H_6) and elevated Methane (CH_4) gas when compared against IEC standards and other diagnostic methods such as California State University Sacremento (CSUS), etc.

Table 4.7: CSUS transformer number 1 gas surveillance guides results

Gas	**Transformer 1 result**	**Normal**	**Elevated**	**Abnormal**
Hydrogen (H_2)	5 ppm	< 150	>150<1000	>1000
Methane (CH_4)	30 ppm	<25	>25<80	> 80
Ethane (C_2H_6)	200 ppm	<10	>10<34	>35
Ethylene (C_2H_4)	1 ppm	<20	>20<100	>100
Acetylene (C_2H_2)	7 ppm	<15	>15<70	>70
Carbon Monoxide as CO	136 ppm	<500	>50<1000	>1000
Carbon Dioxide as CO_2	1118 ppm	<10000	>10000<15000	>15000
Total Dissolved Combustible Gases (TDCG)	720	<720	>720<5000	>5000
Nitrogen (N_2)	45053 ppm	1-10%		
Oxygen (O_2)	105 ppm	0.2-3.5%		

The dissolved gas analysis results were also compared to the CSUS diagnostic method and found to be operating as indicated in Table 4.7 above. It is evident that the transformer number 1 dissolved gas content behaviour pattern for Ethane (C_2H_6) and Methane (CH_4) gas is not normal. Figure 4.5 below shows the results of nine gases and TDCG of transformer 3 monitored at KDS for this research study.

4.3.1.2 Transformer number 3 DGA results and discussion at research site KDS

The eight gases are the same gases monitored in transformer number 1. It is important to indicate that N_2 gas is not included in the graph shown in Figure 4.5.

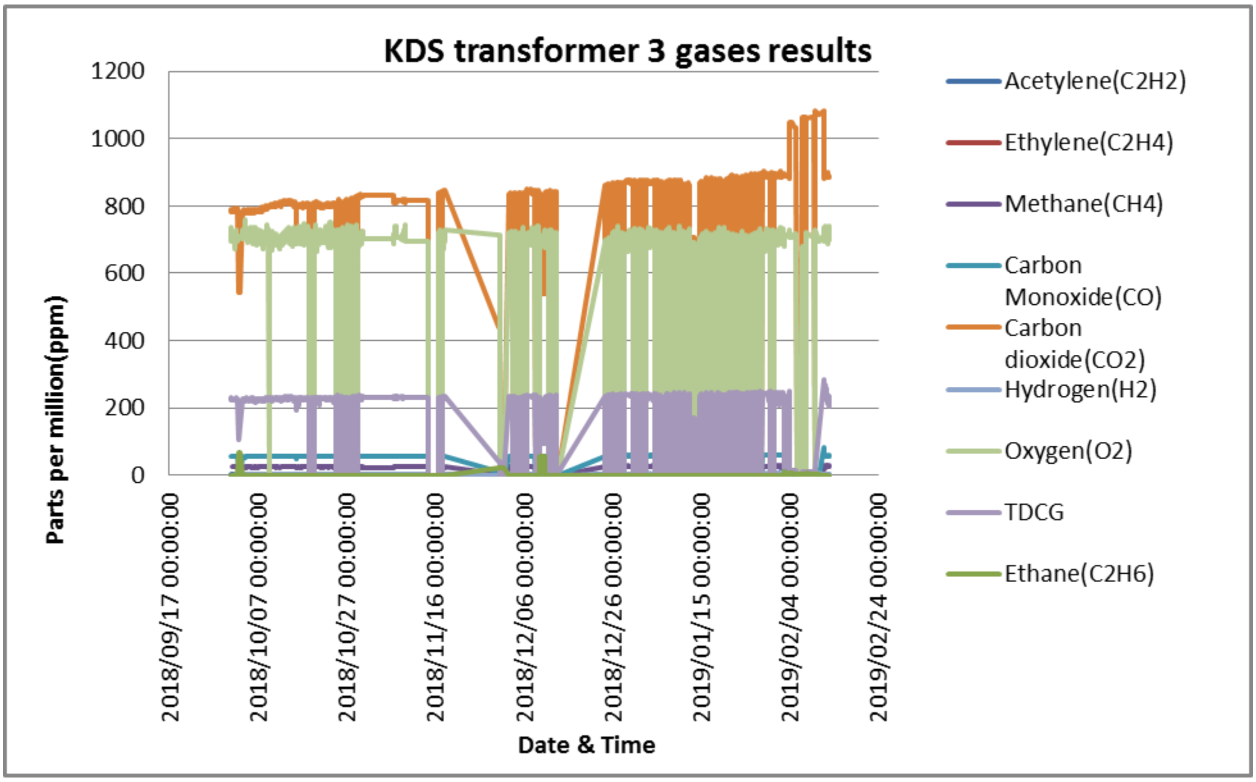


Figure 4.5: KDS transformer number 3 gases trend

The transformer number 3 dissolved gas analysis results as shown in Figure 4.5 above indicate abnormal Ethane (C_2H_6) and elevated Methane (CH_4) gas when compared against IEC standards and other diagnostic methods such as CSUS, etc.

Table 4.8: CSUS transformer number 3 gas surveillance guides results

Gas	**Transformer 3 result**	**Normal**	**Elevated**	**Abnormal**
Hydrogen (H_2)	5 ppm	< 150	>150<1000	>1000
Methane (CH_4)	30 ppm	<25	>25<80	> 80
Ethane (C_2H_6)	200 ppm	<10	>10<34	>35
Ethylene (C_2H_4)	1 ppm	<20	>20<100	>100
Acetylene (C_2H_2)	7 ppm	<15	>15<70	>70
Carbon Monoxide as CO	136 ppm	<500	>50<1000	>1000
Carbon Dioxide as CO_2	1118 ppm	<10000	>10000<15000	>15000
Total Dissolved Combustible Gases (TDCG)	720	<720	>720<5000	>5000
Nitrogen (N_2)	45053 ppm	1-10%		
Oxygen (O_2)	105 ppm	0.2-3.5%		

The dissolved gas analysis results were also compared to the CSUS diagnostic method and found to be operating as indicated in Table 4.7 above. It is evident that the dissolved gas content behaviour pattern for transformer number 3 for Ethane (C_2H_6) and Methane (CH_4) gas is not normal.

The dissolved gas content behaviour pattern of both transformers number 1 and 3 looks exactly the same. Based on the results history, all the combustible gases are well below the typical production rates, except for Ethane (C_2H_6) and Methane (CH_4) levels being higher than normal (see Table 4.7 and 4.8). The carbon oxide gases such as Carbon Monoxide and Carbon Dioxide are both below normal levels. The Total Dissolved Combustible Gas

(TDCG) value is also well below limits. Other analysis techniques such as Duval Triangle and ratio methods (Doernenburg, Rogers and IEC) could not be used, as gas concentration levels are too low.

The current Eskom Distribution maintenance strategy is to sample the power transformers at least once a year. The risk with annual routine oil sampling is that prior to routine sampling the engineers are relying on the previous year’s results. Much can happen in a period of one year pertaining to the health of the transformer while the team is waiting to sample for the next financial year. The transformer diagnostic online condition monitoring unit will provide data measurement when there is a change in the parameter 24 hours a day.

4.3.2 Bushing condition monitoring results

Bushings are a critical component in electricity transmission. Bushings are used in all places where the clearance in a normally insulating medium such as air is insufficient to allow an energised conductor to pass through it without causing a flashover. Regardless of the root cause of failure, the result is often catastrophic [36].

When a bushing fails catastrophically, there is a violent explosion propelling large broken pieces of porcelain several metres at velocities enough to embed the material in concrete walls and destroy neighbouring bushings. Often an explosion is accompanied by a fire that destroys the transformers. To verify the integrity of the insulation during manufacturing, the bushings must pass a series of dielectric tests from high voltage to withstand insulation quality measurement.

With modern measurement technology, the bushing insulation quality can be quantified online by measuring partial discharges and dissipation factors. These tests, particularly insulation quality measurement, are performed in a controlled environment in order to eliminate background noises and to establish accurate readings [36].

In the field, bushings are subjected to a number of routine inspections and tests to verify the operational condition, and to monitor its ongoing fitness for service. Normally the location, environment and available measurement devices limit the scope and magnitude of electrical tests. One of the commonly employed methods for insulation inspection in the field is the measurement of the bushings power factors. Based on a collection of power factor values, an assessment can be made on the operating condition of the bushing. In this research paper, the technique for bushing capacitance, dissipation factor and voltage measurements using online bushing monitoring technology will be introduced.

The current maintenance strategy in Eskom Distribution is covering only the testing of dissipation factor (Tan Delta) and capacitance in the bushings. Bushing Tan Delta and capacitance tests are synchronised with tap changer maintenance. The dissipation factor and capacitance tests are done once in six years in the bushings. The greatest disadvantage of this method is that the power supply to customers is switched off when conducting bushing capacitance and tan delta tests on transformers. The type of bushings fitted in transformers number 1 and 3 for this research study are called Resin Impregnated (RIP) Bushings.

The rapid changes in the insulation due to moisture will not be addressed by the current maintenance strategy, and bushings will fail before they can be tested. The advantages of online monitoring of bushing is the type of data collection the researcher has, and in case any deviation is detected, immediate action can be taken to avoid the transformer resulting in bushing explosions. The results to be discussed in the research are the historical trends of dissipation factor, capacitance and voltages. The historical trend was determined for the period from 1 October 2018 to 13 February 2019.

4.3.2.1 Dissipation factor (Tan Delta) and capacitance results discussion

The condition of the insulation is essential for secure and reliable operation of the transformer. Measuring capacitance and dissipation factor/power factor assists in determining the insulation condition in the bushing. High oil conductivity, ageing and an increase in the water content are symptoms of the degradation process in the insulation [39].

These symptoms also result in an increase of losses, which can be quantified by measuring the power factor or dissipation factor. Changes in capacitance can indicate partial breakdown between the capacitive layers of the bushings. By measuring the capacitance and losses, problems in the insulation can be detected before failure occurs. This research study will assist Eskom Distribution engineers and national control for the first time to receive alarms and warning short message system (SMS) in case where thresholds of capacitance and dissipation factor are exceeded in the bushings.

The data will be retrieved in the server, and the historical trend will be plotted on the graph and analysed. Any rise in capacitance of more than 10% in the trend results will be considered to be dangerous for the bushings. It indicates that a part of the insulation distance is already compromised, and dielectric stress remaining on insulation is too high.

4.3.2.2 Transformer number 1 dissipation factor and capacitance results discussion

Figure 4.6 shows the averaged dissipation factor three phases (red, white and blue) bushings in the primary side of transformer number 1 at KDS.

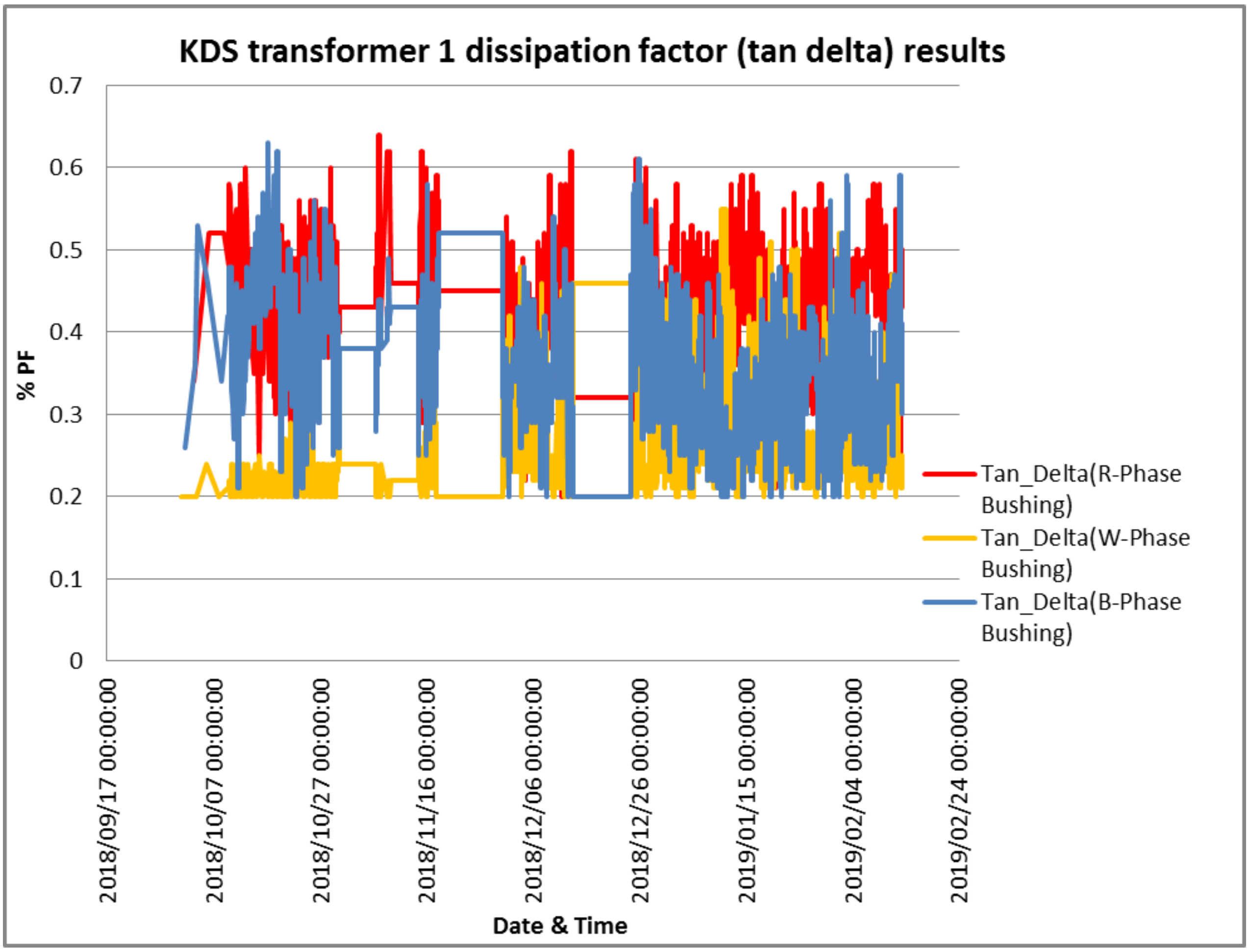


Figure 4.6: Dissipation factor profile of transformer number 1 bushings at KDS

As shown in Figure 4.6 above, the dissipation factor of all three bushings on the primary side of the transformer are regulating beyond the limit of 0.85 %. According to IEEE C57.19.01 the power factor limit for RIP transformer bushings is 0.85 %. The results for three bushings mean that there is no ageing and no insulation breakdown in the bushings.

It can also be seen in Figure 4.7 below that there is no change in capacitance for all three phases (red, white and blue). According to IEEE C57.19.01, the acceptable change in capacitance (%) for RIP transformer bushings is ± 10%. The results indicate that there are no partial breakdowns, voids and cracks in all three bushings.

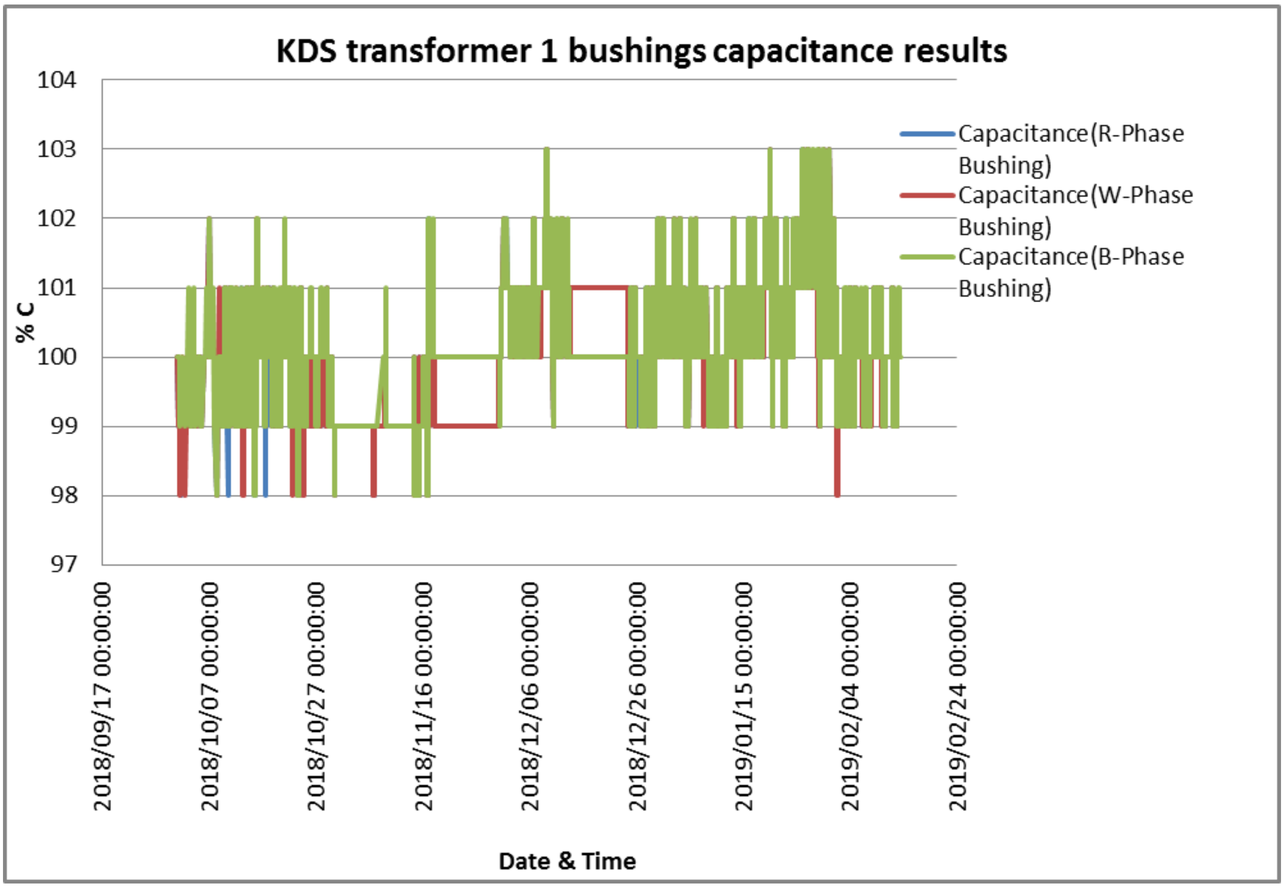


Figure 4.7: Capacitance profile of transformer 1 bushings at KDS

4.3.2.3 Transformer number 3 dissipation factor and capacitance results discussion

Figure 4.8 shows the averaged dissipation factor of three phases (red, white and blue) bushings in the primary side of transformer number 3 at KDS.

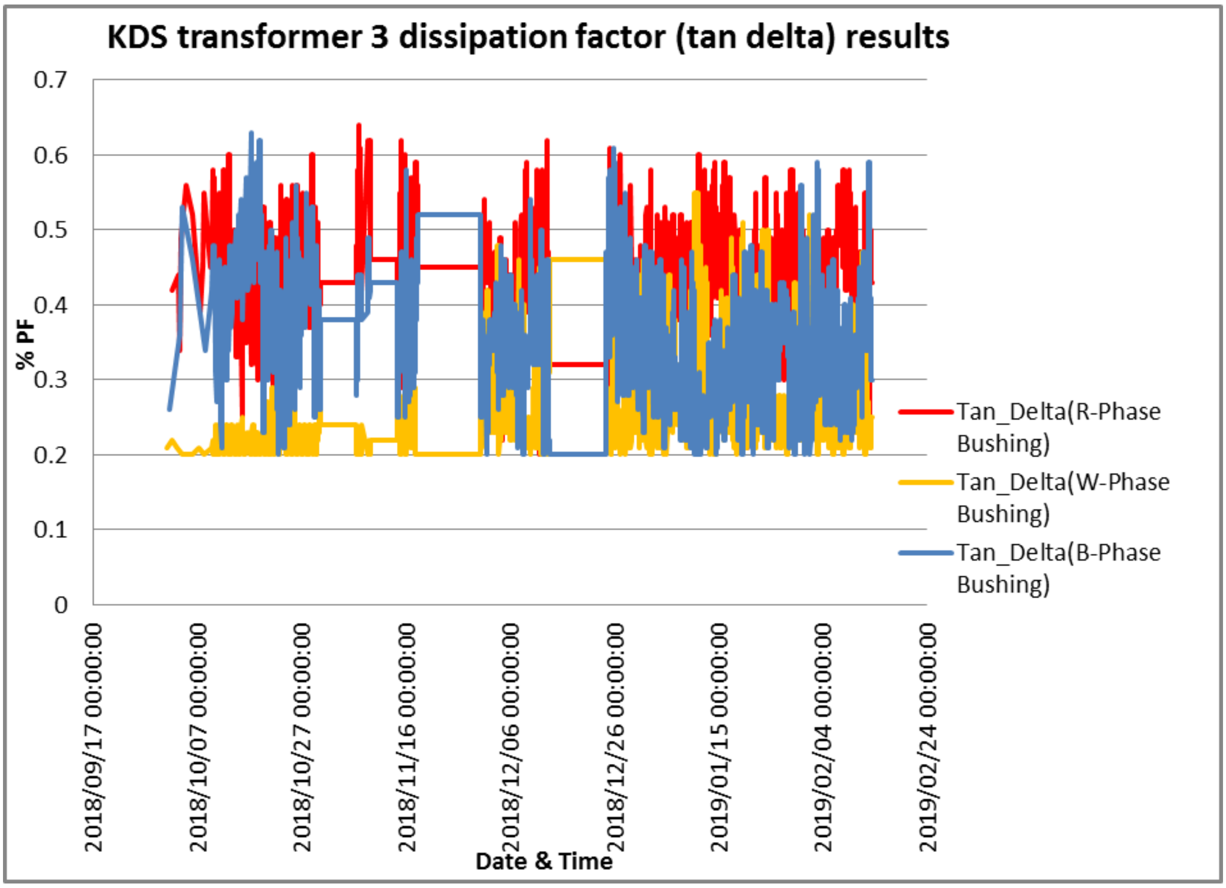


Figure 4.8: Dissipation factor profile of transformer 3 bushings at KDS

As shown in Figure 4.8 above, the dissipation factor of all three bushings on the primary side of the transformer are regulating beyond the limit of 0.85 %. According to IEEE C57.19.01, the power factor limit for RIP transformer bushings is 0.85 %. The results for the three bushings indicate that there is no ageing and insulation breakdown as a result of moisture ingression.

It can also be seen in Figure 4.9 below that there is no change in capacitance for all three phases (red, white and blue). According to IEEE C57.19.01, the acceptable change in capacitance (%) for RIP transformer bushings is ± 10%. The results reveal that there are no partial breakdowns, voids and cracks in all three bushings.

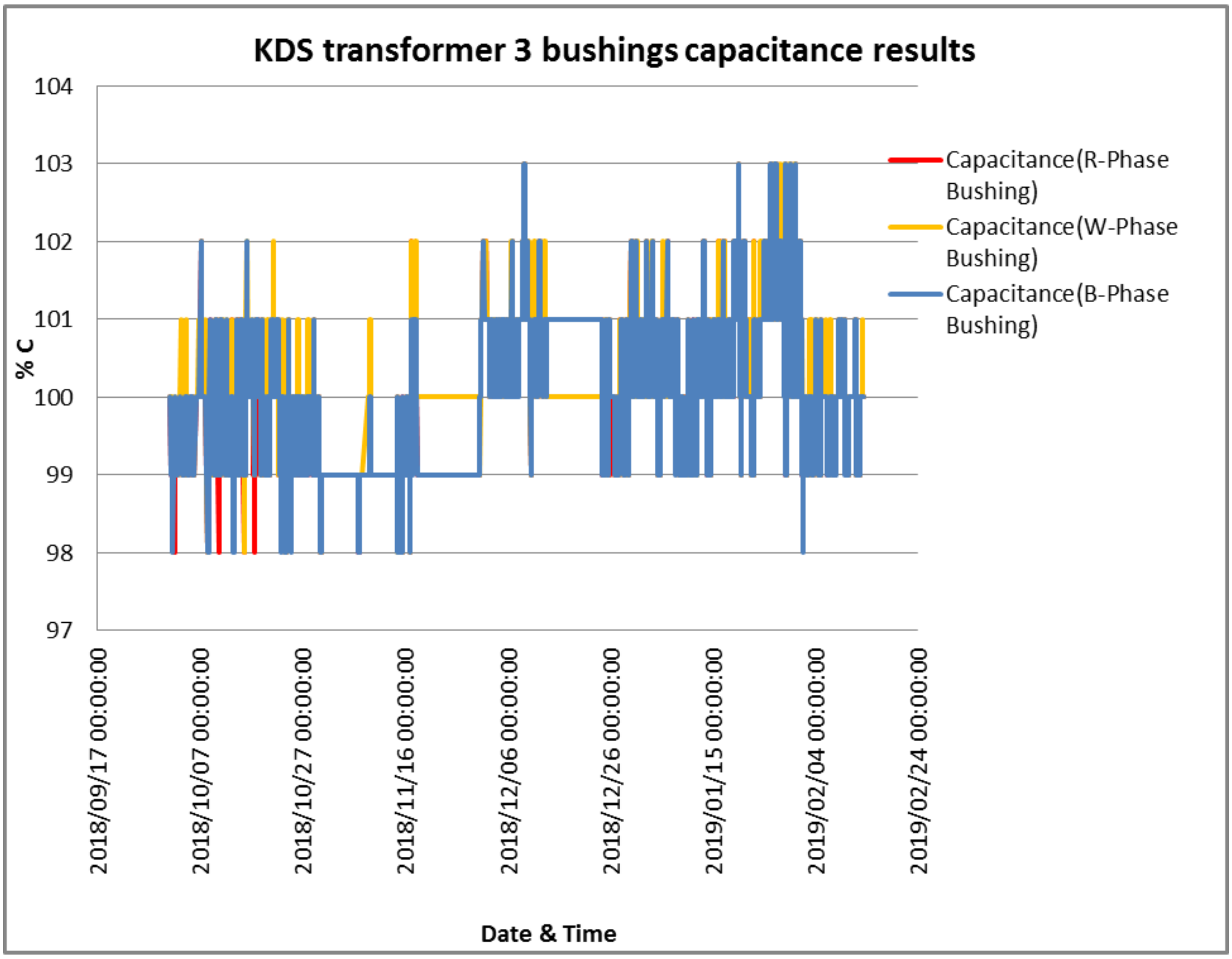


Figure 4.9: Capacitance profile of transformer 3 bushings at KDS

4.3.2.4 Phase voltage results discussions

High-voltage bushings are not only subject to the obvious day-to-day environmental wear, but also to over-voltages, transient effects from the network and exceptional conditions such as lightning strikes, which may all be causes for unforeseeable damage. The bushings are designed to withstand exceptional forces, which means that the transformer will not be immediately damaged [20].

Therefore, an important item in condition monitoring is close analysis of the bushing condition, currents and voltages. For transformers, measurement of red, blue and white voltages provides the option to detect degradation of the bushing, such as disruptive discharges between two adjacent layers of capacitors. This can be accomplished by comparing the results with each other [20].

Bushing failures usually occur in a sequence of small defects which impose the loss of intermediary capacitive layers, frequently caused by short-circuit between two conductive aluminium sheets. This progression is irreversible and provokes the elimination of one capacitive layer, thus causing an increase in the overall capacitance of the bushing. By monitoring the voltage or current on the capacitive tap (voltage or test tap) of the bushings, it is possible to verify the variation on the capacitance relative deviation between the phases, and to identify a possible fault [10].

The higher the voltage levels, the higher the risk of bushing failures. The 24-hour data will be stored in the server for trending and for historical purposes on phase voltages. The data will be analysed, and a recommendation will be made based on the results of the phase voltages. The data will be retrieved in the server, and the historical trend of the high-voltage bushings in all three phases will be plotted in the graph. Any relative deviation between the phases of more than ±5% in the trend results will be considered to be dangerous, and a possible fault will be identified in the bushings. According to the NRS 048-2:2015, voltage regulation lower and upper limits are set at -5 % and +5 % of declared voltage.

4.3.2.4.1 Transformer number 1 bushings phase voltage results discussion

Figure 4.10 shows the averaged phase voltage of three bushings (red, white and blue) in the primary side of transformer number 1 at KDS.

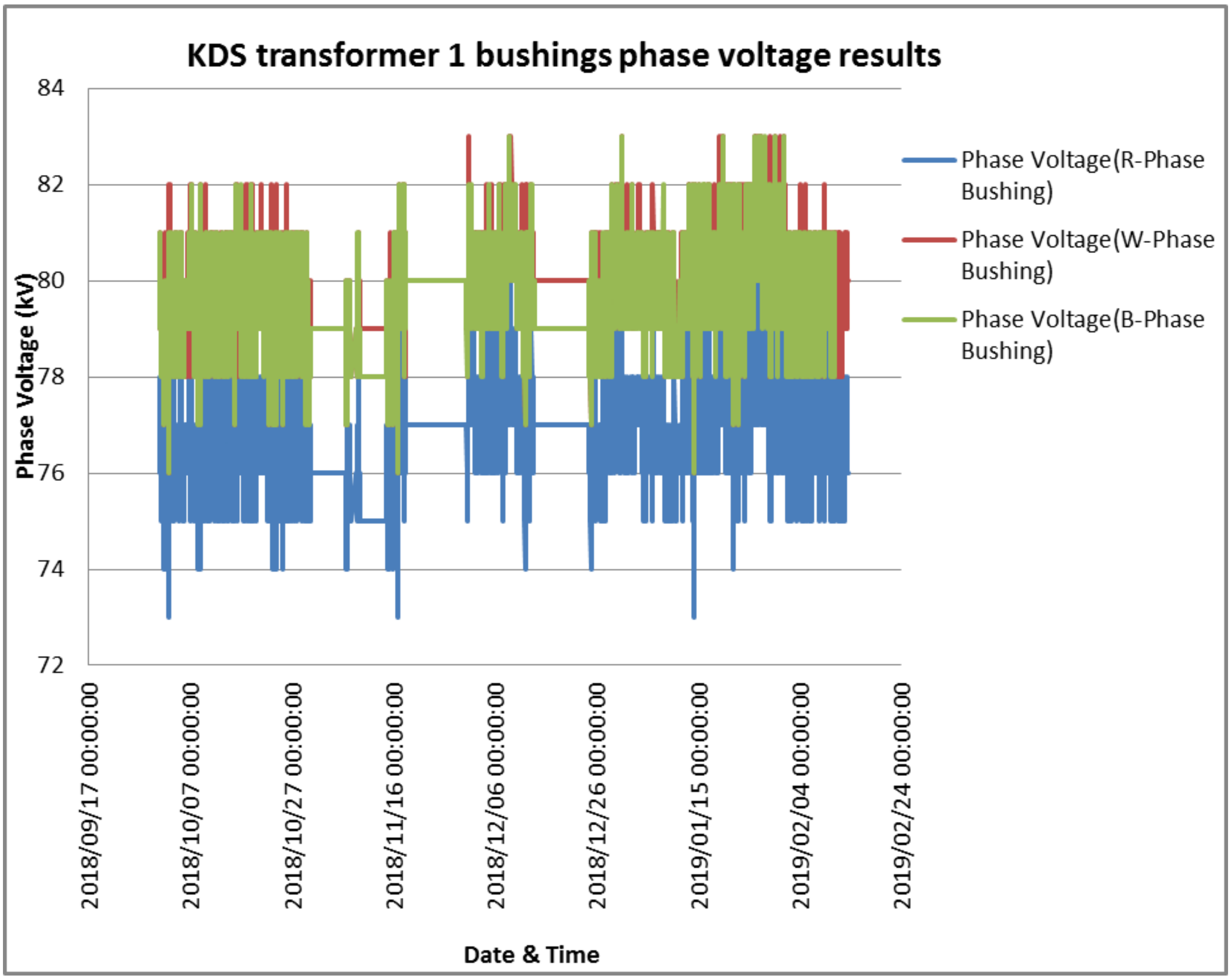


Figure 4.10: Phase voltage of three bushings in the primary site of transformer 1

As shown in Figure 4.10 above, the red phase voltage is regulating within the voltage regulation lower and upper limits of ±5%. The white and blue phases are at times regulating slightly above the upper limit of +5%. However, this is not a major issue, as it happens occasionally. From the results above it is clear that the danger of recording higher voltage levels for a longer period that may result in the risk of bushing failures is very low.

4.3.2.4.2 Transformer number 3 bushings phase voltage results discussion

Figure 4.11 shows the averaged phase voltage of three bushings (red, white and blue) in the primary side of transformer number 3 at KDS.

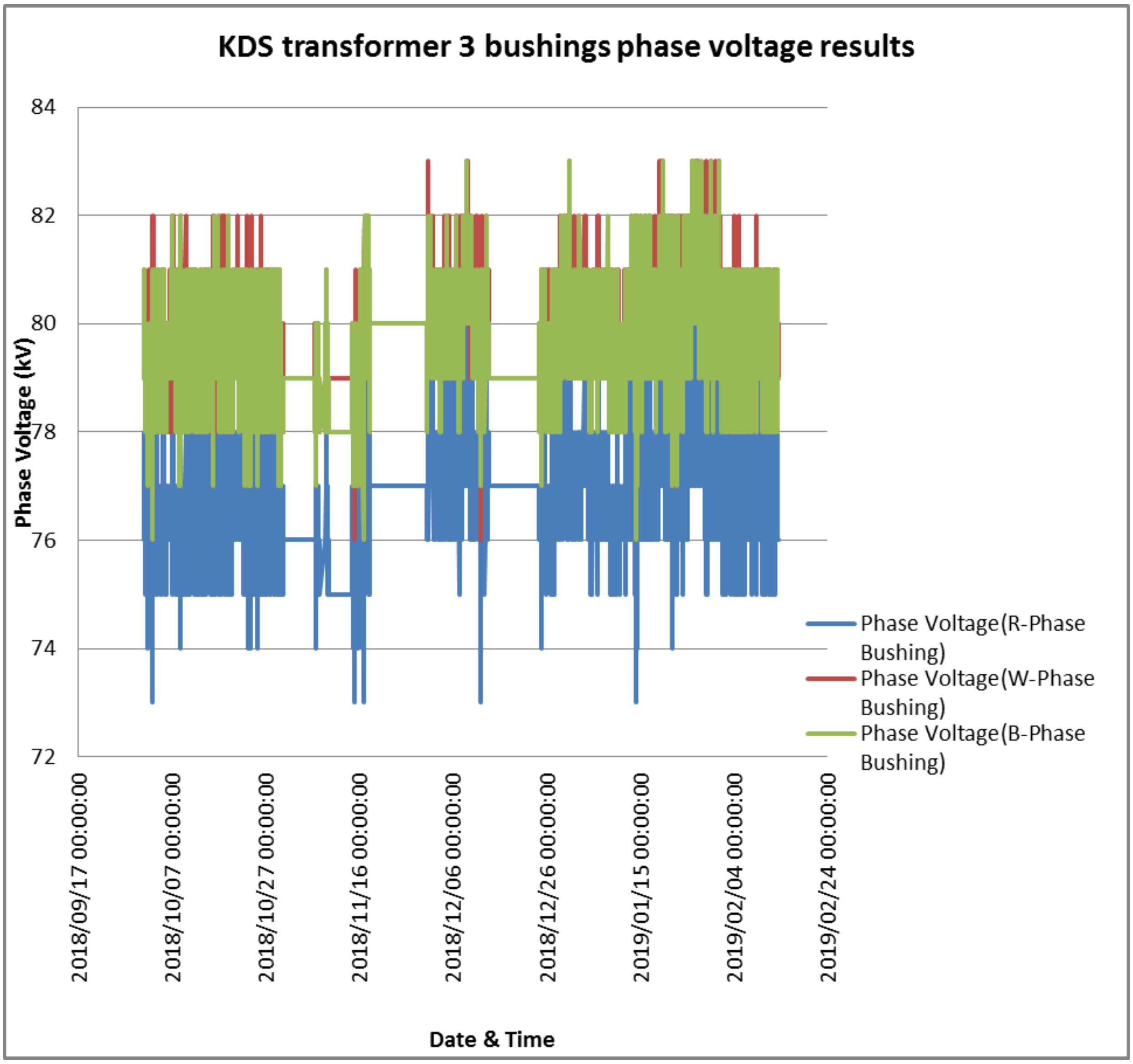


Figure 4.11: Phase voltage of three bushings in the primary site of transformer 3

The bushings phase voltage behavioural pattern of transformer number 3 is similar to that of transformer number 1. As can be seen in Figure 4.11 above, the red phase voltage is regulating within the voltage regulation lower and upper limits of ±5%. The white and blue phases are at times regulating slightly above the upper limit of +5%. However, this is not a major issue, as it only occurs occasionally. From the results above it is clear that the danger of recording higher voltage levels for a longer period which may result in the risk of bushing failures is very low.

From the results it can be concluded that the HV bushings of transformers number 1 and 3 are in a good condition. It is very important to highlight that the current Eskom Distribution maintenance strategy is not covering the testing of phase voltages in the bushing. The phase voltages cannot be tested, as the transformer is switched off completely to conduct capacitance and dissipation factor offline tests in the bushings. The technology introduced in this research will be able to assist Eskom Distribution in measuring the phase voltages online.

4.3.3 Temperature, load and ageing monitoring results

Higher operating temperatures (due to loading) and ambient temperatures affect the overall condition of the transformer. Normal operating and ambient temperatures have been accounted for in the design and construction, but abnormal conditions could cause gradual deterioration of the transformer internals and the outside auxiliaries.

Temperatures above those recommended by the vendor and the IEEE Standard C57.91-1995 could accelerate the deterioration of the insulating liquid and jeopardise the life expectancy of transformers [24].

Top oil temperature, winding hot spot temperature and ambient temperature results will be monitored and analysed in this research study for normal operating conditions. The ageing process is minimal if the oil and paper are kept dry, the oxygen content is nominal and the hot-spot temperatures are not above standard allowances. If the transformer temperature does not exceed the rating of the paper, it is possible to load the transformer at or above its rating depending on the ambient temperature without significant loss of life [24].

Failure can result from thermal ageing if the transformer is overloaded to the extent that hot-spot temperatures above the rating of the paper occur for long periods of time. Damage to the paper can also result from operation for long periods of time without cooling. In the research site, the winding temperature alarm of both transformers 1 and 3 is set at 110°C, whilst the winding temperature trip is set at 120°C. The oil temperature alarm is set at 85°C, and the oil temperature trip value is set at 95°C.

The graph in Figure 4.12 below shows the temperature results. The historical temperature trend is indicated for the period 1 October 2018 to 13 February 2019. The historical data results depicted in Figure 4.12 are for transformer number 1 at KDS. The historical data of three temperatures, namely ambient, winding and top oil were recorded for a period of four months and retrieved. The data of transformer 1 at KDS will be analysed to predict power transformer failure in this research study.

It can be clearly seen in Figure 4.12 (transformer 1) below that there is a positive correlation between the three temperatures (ambient, winding and top oil). When ambient temperature increases, the winding temperature and top oil temperature also increases. The historical data results depicted in Figure 4.12 are for transformer number one at KDS.

It is evident from the results that a drop in ambient temperature results in a decrease in winding and top oil temperatures. At some instances the winding and top oil temperatures both decrease, while the ambient temperature remains constant or increases. This is because cooling fans (oil natural air forced) switch on to protect the windings against the extremely high temperatures.

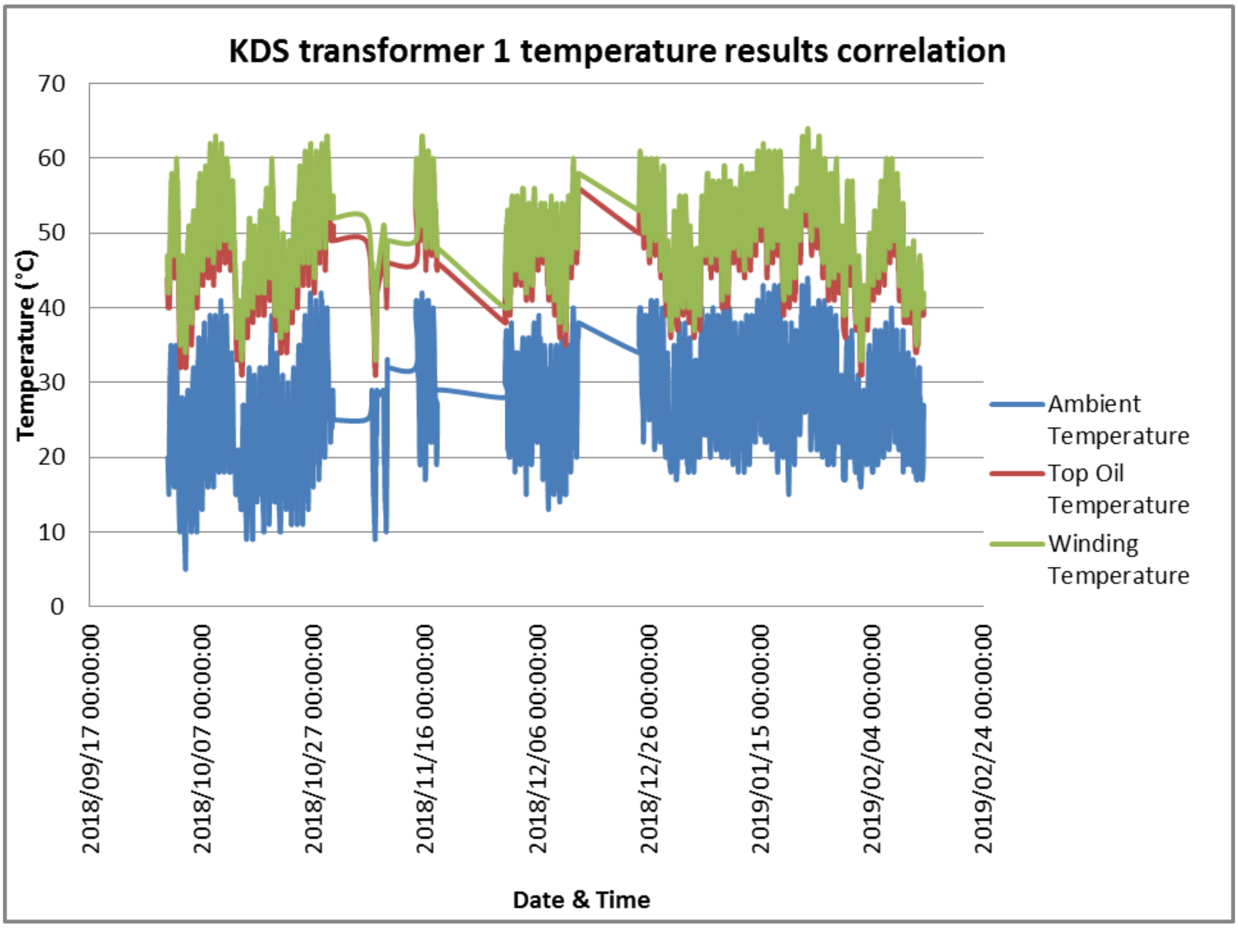


Figure 4.12: Temperature profiles of transformer number 1 at KDS

It can also be seen in Figure 4.13 below that when ambient temperature increases, the winding temperature and top oil temperature also increases. The same pattern was recorded for transformer number 1. It is very important to consider the ambient temperature when designing the transformer to avoid failures. The historical data results depicted in Figure 4.13 are for transformer number three at KDS.

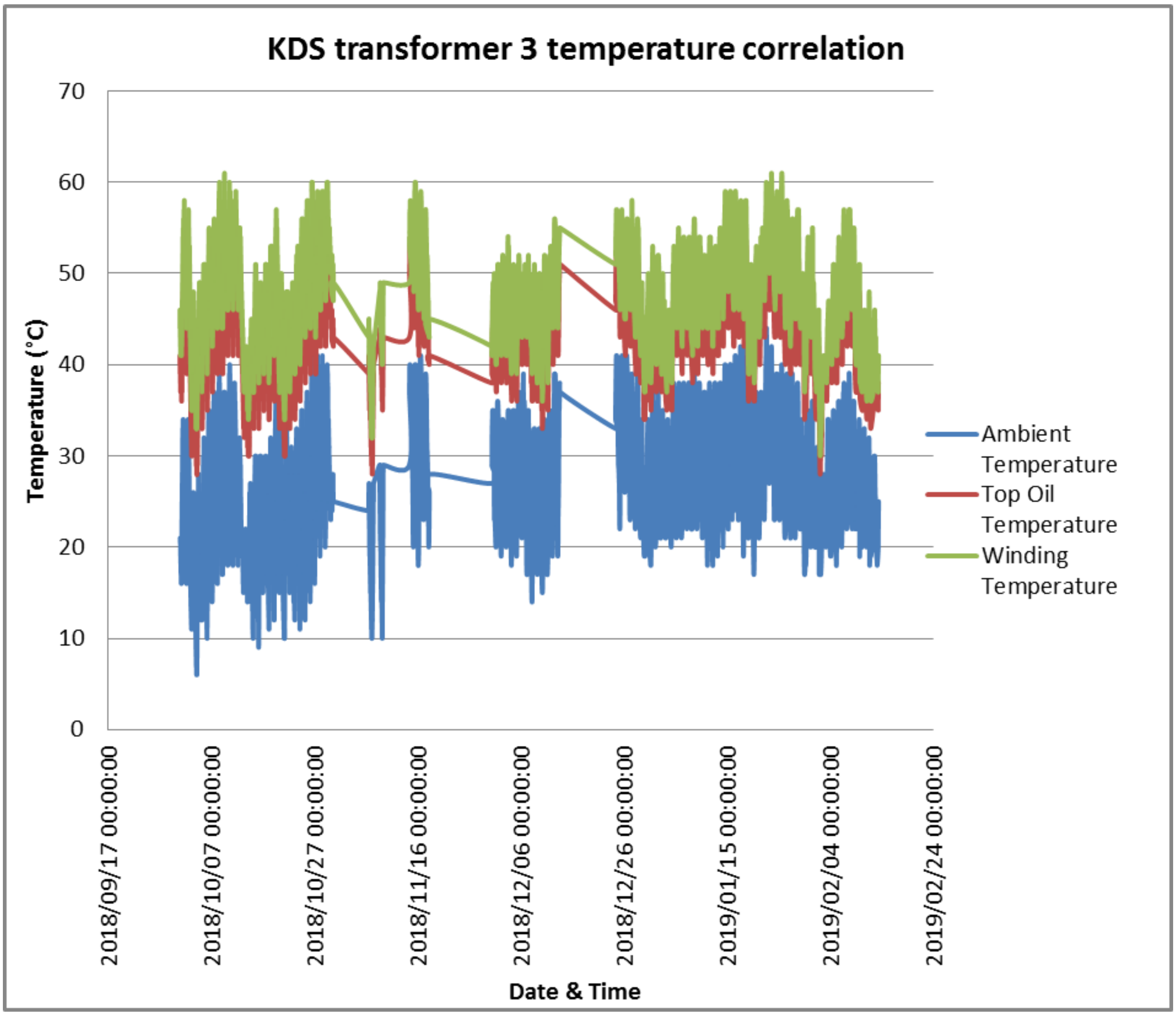


Figure 4.13: Temperature profiles of transformer number 3 at KDS

It is also important to mention that with the current data collection methods the ambient temperature is not measured in Eskom Distribution substation. Eskom Distribution only relies on the alarms and the tripping of the winding and oil top temperatures. In this research study it can be seen that the ambient temperature historical data is very crucial to be measured, collected and stored in the server.

As can be seen in Figure 4.12 and Figure 4.13, the ambient temperature has an effect in increasing the hot spot temperature above the rating of the paper, without overloading the transformer. This may result in the failure of the transformer insulation due to the extreme increase in the ambient temperature. It will be emphasised in Chapter 5 when performing an analysis of the research results how critical the ambient temperature can be, and how it can influence the heat increase in the transformer without increasing the loading.

4.3.4 Cooling fans monitoring results discussion

The research study will only focus on the Oil Natural Air Forced (ONAF) cooling method. The cooling radiators have fans externally mounted on the transformer. Blowing air through the radiators ensures a better heat transfer, as the hot air next to the radiators is forcibly replaced by cooler air. Normally, the fans are fitted below the radiators and blow surrounding air vertically upwards between the radiators.

It is important to indicate that there is no maintenance strategy currently in Eskom Distribution covering the cooling fans on the transformers. If the cooling fans are not working correctly due to any unforeseen reason, it will not be detected. If the cooling fans are not working properly, it significantly impacts on the transformer's lifespan and ability to be loaded. The technology introduced in this research study as shown by the results will be able to assist in detecting if the fans are operational by measuring the current in all three fans. The data from the fans will then be analysed to ensure that they are still operating correctly when required.

Figure 4.14 below shows fan 1 and fan 2 of transformer number 1 operating correctly when the winding temperature increases. Fan 1 and fan 2 operated mostly at the same time, and fan 3 never operated in the chosen period. It can be further seen in Figure 4.14 below that during periods of low load or low ambient temperature, the fans were not running. During the periods of high loading or high ambient temperature fans were normally activated by a contact on the winding temperature gauge. The measurement of fans current in the research study is necessary to verify the correct operation of each fan. The historical fans current (amps) trend is indicated for the period 1 October 2018 to 13 February 2019.

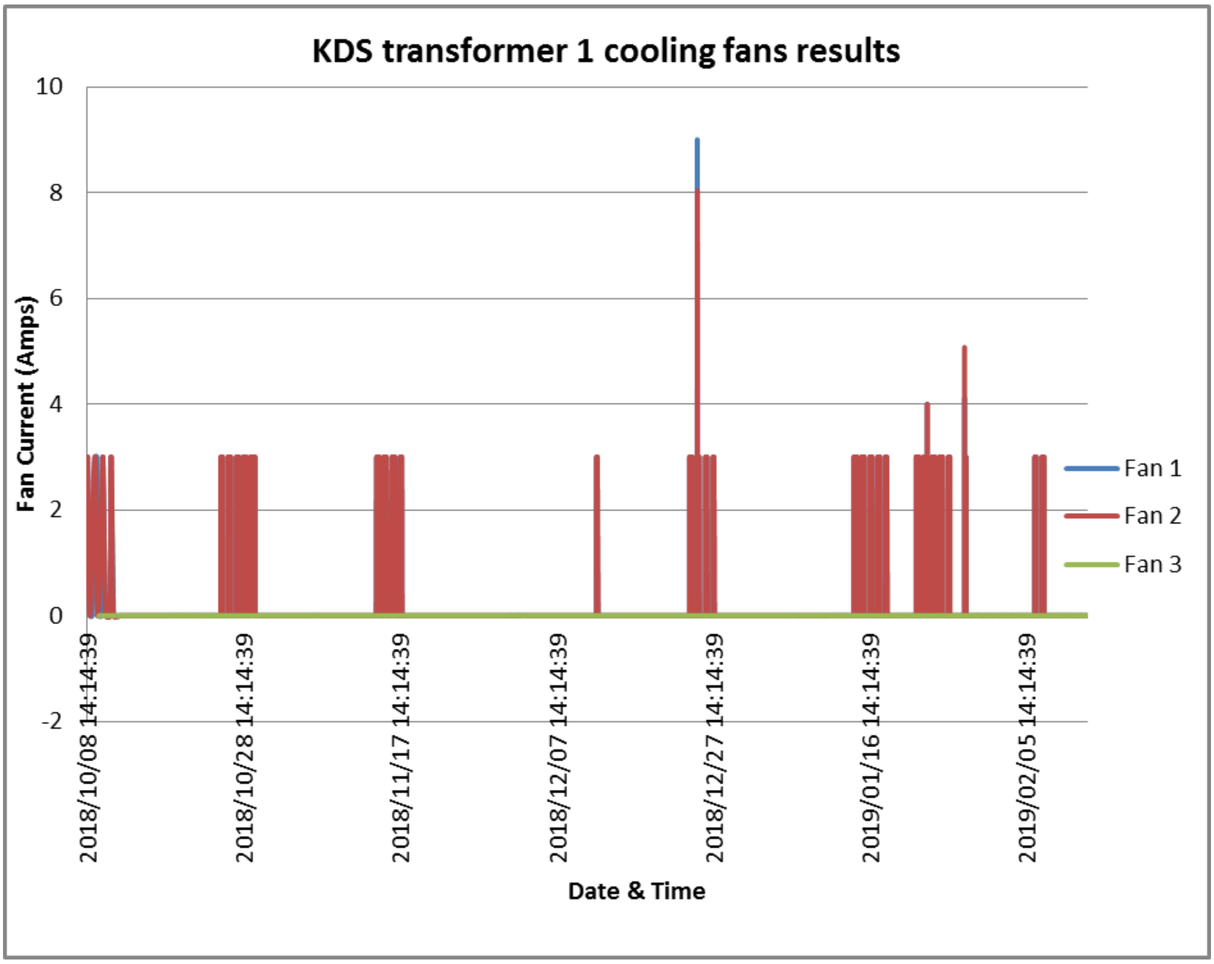


Figure 4.14: Fan current profiles of transformer number 1 at KDS

It can also be seen in Figure 4.15 below that most of the time fan 1 and fan 2 operated simultaneously, whilst fan 3 never operated in the chosen period. It is important to highlight that at some point in transformer 3, fan 1 operated alone for certain periods, whilst in transformer 1 fan 1 and 2 operated at the same time. It can further be seen in Figure 4.15

below that during periods of low load or low ambient temperature the fans were not operational.

During periods of high loading or high ambient temperature fans were normally activated by a contact on the winding temperature gauge. The winding temperature is critical because the process of switching on the fans is depending on it. The higher the winding temperature recorded, the more fans will automatically switch on to provide cooling in the transformer.

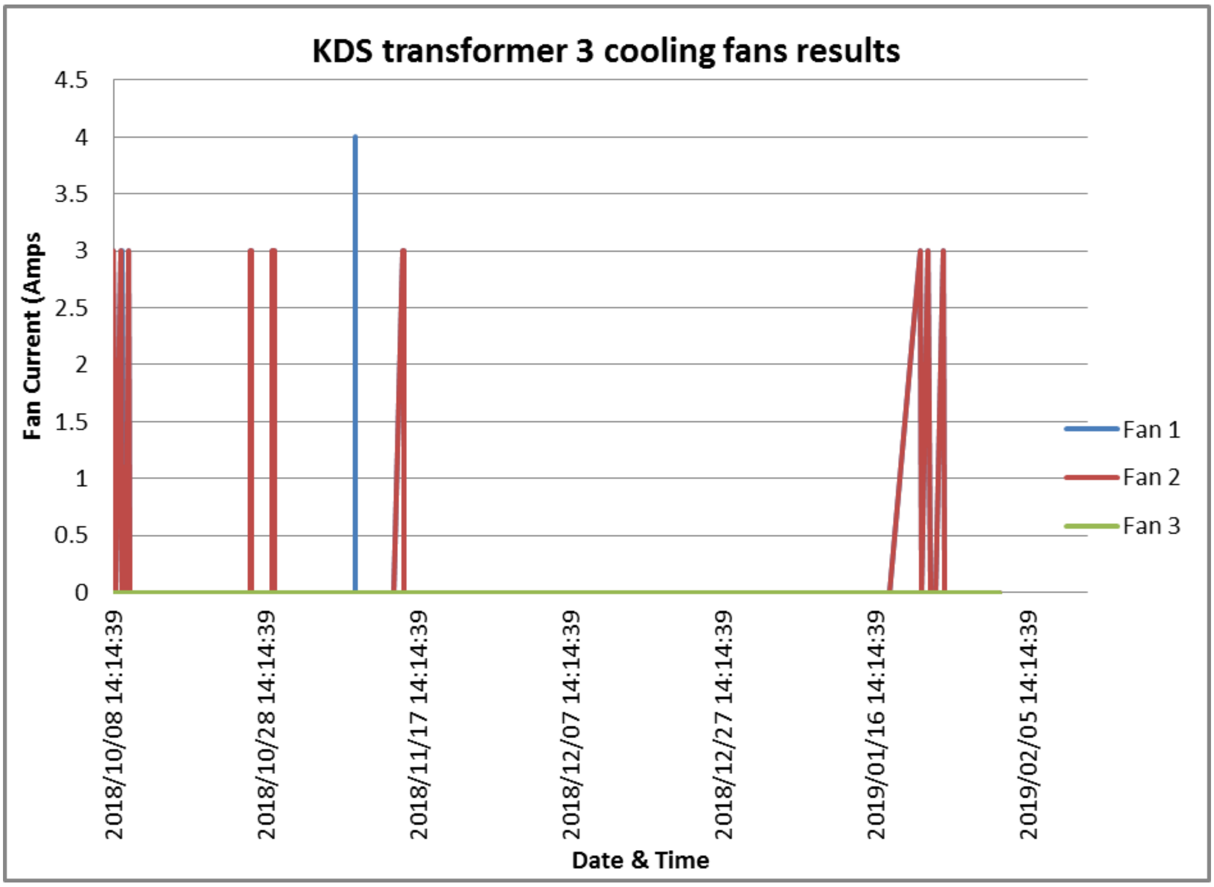


Figure 4.15: Fan current profiles of transformer number 3 at KDS

Figure 4.14 and Figure 4.15 above illustrate that the fans of transformer 1 and 3 at KDS are operating correctly. The fans were switching on when winding temperature reached a predetermined setting (in degrees Celsius). From the results shown above it can be clearly seen that in the hot areas such as the Northern Cape the transformers should be fitted with an ONAF cooling method.

The results show that the fans were operating on a regular basis to cool the two transformers when required. The Oil Natural Air Natural (ONAN) cooling method will not be adequate in hot areas because of the high ambient temperatures associated with these areas most of the time, and a forced air-cooling method will be more appropriate. It is evident from this study that it is critical to ensure that the fans are operating as they should by monitoring them.

If the fans are not monitored it will be difficult to identify if they are still operating correctly. It is important to highlight that, should the cooling fans fail when the preset conditions are met, the lifespan of the transformer as well as the loading capabilities will be negatively affected. The monitoring of the fans ensures that transformers are not overloaded when the fans malfunction.

4.3.5 On-load tap changer condition monitoring results discussion

The failure of tap changers contributes significantly to transformer failures and poor reliability. The electrical plant is ageing, and it is important to implement the best technologies available to improve the service life of tap changers in order to avert more failures. The objective of the research was to introduce the tap changer condition monitoring techniques which were identified to be suitable to increase the service life and prevent failures of tap changers.

The results in Figure 4.16 below highlight the benefits that can be drawn from using the transformer online condition monitoring techniques.

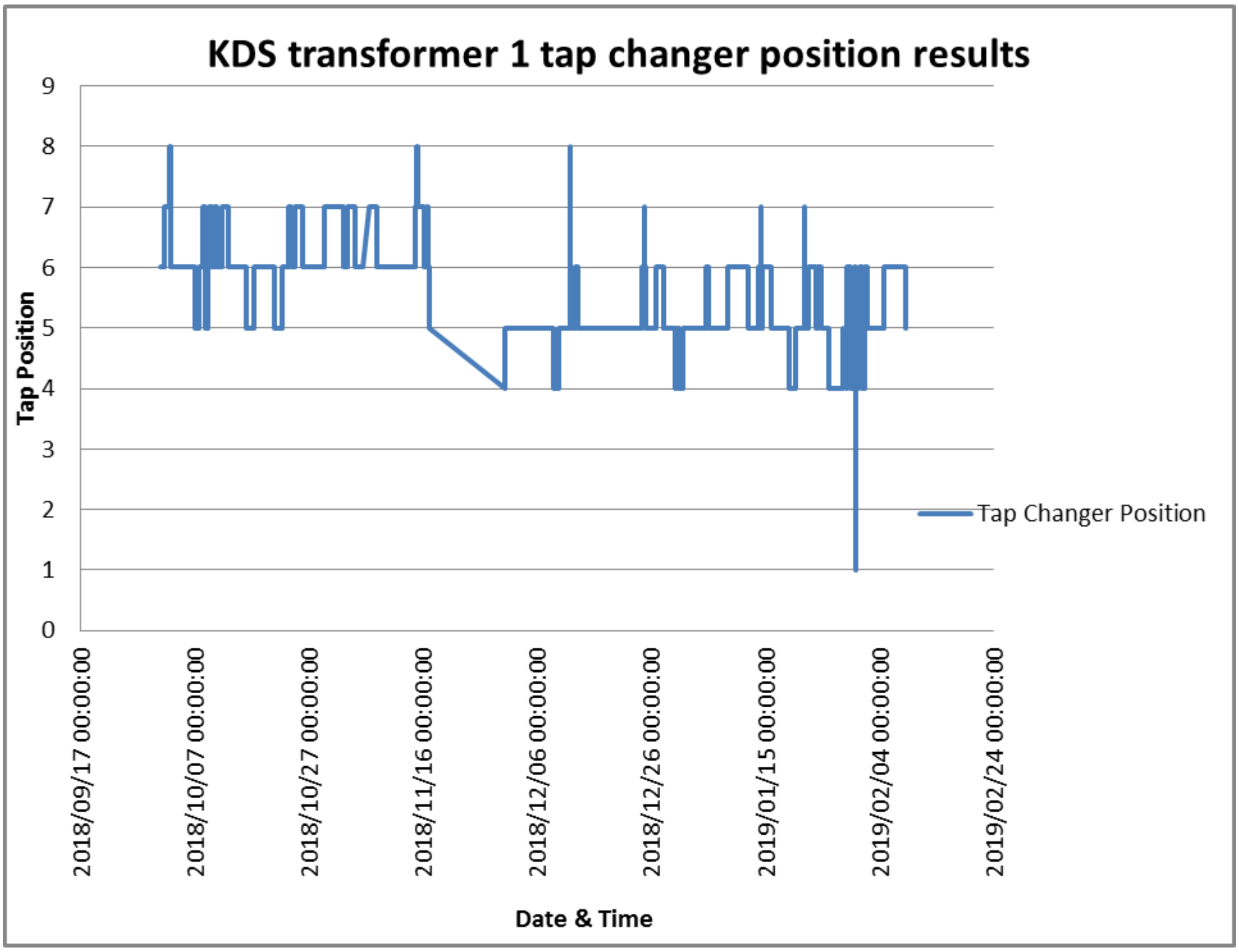


Figure 4.16 Tap changer positions of transformer number 1 at KDS

The results in Figure 4.16 above show that in the final three months the tap changer operated between tap 4 and tap 8 positions most of the time on transformer number 1 at KDS. At some point it can be seen from the results above that the transformer was on tap 1 position, but for a short period of time. It is important to mention that positions between tap 4 and tap 8 comply with the NRS 048-2:2015 voltage regulation lower and upper limits.

Figure 4.17 below shows the tap position results for the period 1 October 2018 to 13 February 2019 for the tap changer of transformer number 3 at KDS. It operated between tap 4 and tap 8 positions most of the time. Unlike transformer number 1, transformer number 3 tap changer never operated up to tap 1 position.

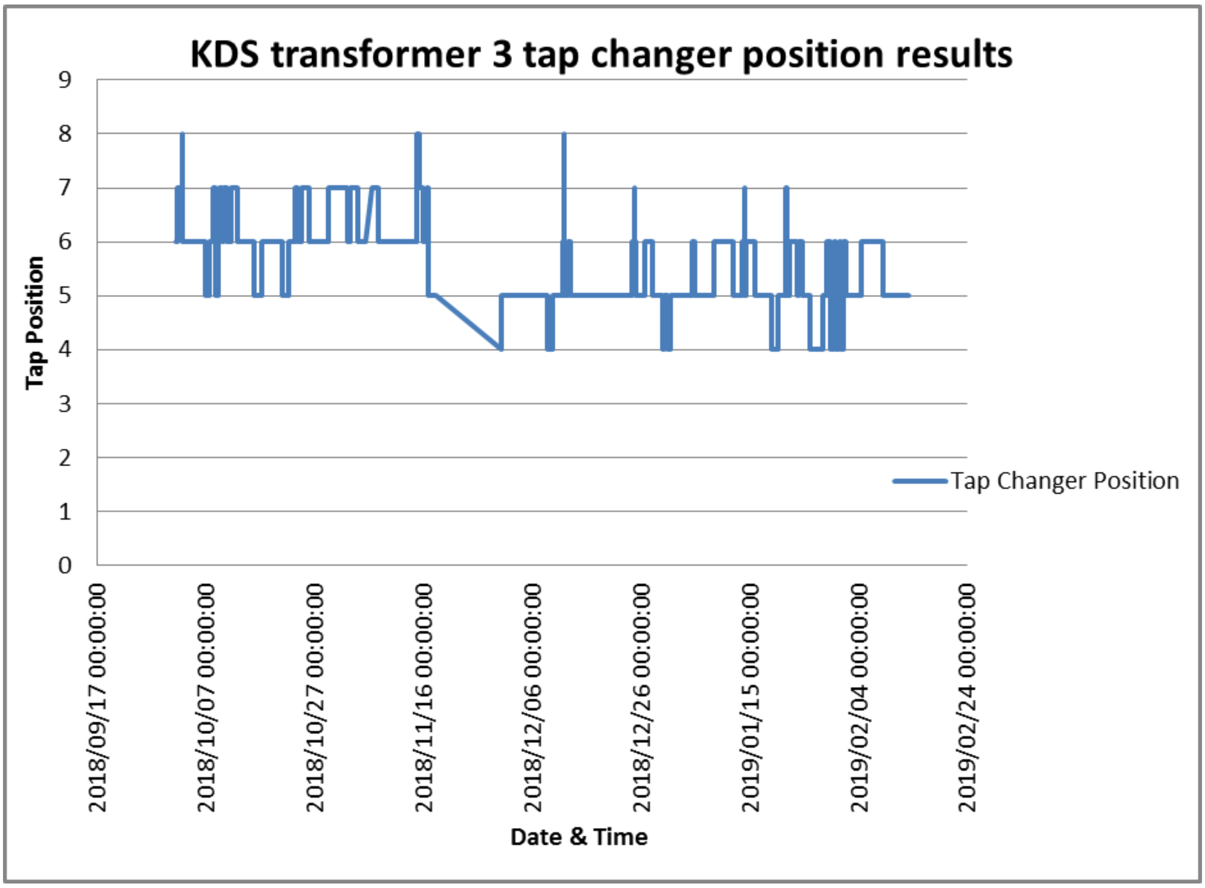


Figure 4.17: Tap changer positions of transformer number 3 at KDS

It is good to see from the results that transformer number 3 was tapping between tap 4 and tap 8 for the entire period. It is important to mention that positions between tap 4 and tap 8 comply with the NRS 048-2:2015 voltage regulation lower and upper limits. The advantage of not tapping in one tap position most of the time is that the tap changer contact wear will be minimal because the tap changer is also using other contacts. The monitoring of tap changer positions ensures the voltage regulation is regulating within the compatibility levels of the NRS 048-2:2015.

4.3.6 Conclusion

In this chapter, it was indicated how historical data were retrieved from the transformer by means of online monitoring, and how data were utilised to trend results and establish the possible failure or major faults on power transformers. Transformer online condition monitoring can be used by sectors such as municipalities and electrical utility companies to monitor the asset health of their power transformers.

It is evident from the discussion of different results parameters that the use of transformer online monitoring system proved to be effective in assisting with the detection of major faults in power transformers. Power transformer failure is usually considered as a major cause for unplanned outage. Ensuring good conditions of HV bushings, tap changers, active parts, cooling and temperatures are of vital importance to maintain power supply reliability. However, some industry statistics show that 80% of equipment failure incidents happened randomly and were not detectable during common testing and maintenance.

It has been observed that most of the utilities sample the oil on power transformers at least once a year. The risk with annual routine oil sampling is that prior to routine sampling the engineers rely on the previous year’s results. Much can happen in a period of one year pertaining to the health of the power transformer while the team is waiting to sample for the next financial year. From the transformer diagnostic online condition monitoring used, we saw that it provides data measurements by oil sampling 24 hours a day.

Furthermore, it was evident that the ambient temperature has an effect on increasing the hot-spot temperature above the rating of the paper, without overloading the transformer. This may result in the premature failure of transformer insulation due to the extreme increase in the ambient temperature.

It has also been found that most of the utilities are covering only the testing of dissipation factor (Tan Delta) and capacitance in the bushings, excluding phase voltages in the HV side. Bushing Tan Delta tests are synchronised with the tap changer maintenance. The dissipation factor tests are done once in six years in the bushings. It was discovered that the disadvantage of this maintenance strategy is the unknown condition of the bushing until the maintenance period arrives. Furthermore, power supply to customers is cut off when conducting bushing tan delta tests on transformers, as an outage is needed.

The maintenance strategy of the utilities ignores the importance of monitoring the cooling fans on the transformers. If the cooling fans are not working correctly due to any unforeseen reasons, this type of fault will not be detected. If the cooling fans are not working correctly, this impacts significantly on the transformer's lifespan and ability to be loaded.

CHAPTER 5: ONLINE CONDITION MONITORING RESULTS ANALYSIS

5.1 Online condition monitoring results analysis

In this chapter the results analysis of online condition monitoring transformer parameters are discussed in detail. In this research the data were retrieved directly from the online condition monitoring server. The study aims to investigate the usage of transformer online condition monitoring to predict potential power transformer failures.

5.1.1 Dissolved Gas Analysis results of transformer number 1 at KDS

The Dissolved Gas Analysis (DGA) results of transformer number 1 at the Kimberley Distribution Substation (KDS) will be analysed in this section. As per the IEC 60599:2007, combustible gases are well below the normal levels (see extract from Specification in Annexure A showing the typical concentration levels) based on the results retrieved by using online condition monitoring technology. Refer to Table 5.1 for the results. The only gas considered abnormal based on the results is Ethane (C_2H_6).

Based on the historic trend of the results retrieved for this research study, all the combustible gases are well below the typical rates, except for C_2H_6 being slightly higher than normal (see Table 5.2 and 5.3). The carbon monoxide and carbon dioxide concentrations are both below the typical normal levels. The Total Dissolved Combustible Gases (TDCG) value is also well below limits.

As indicated in Chapter 4 of this research study, other analysis techniques such as Duval Triangle and ratio methods (Doernenburg, Rogers and IEC) could not be used, as gas concentration levels were too low.

Table 5.1: Results analysis of DGA transformer 1 at KDS

	Gas detected in sample (ppm)					IEC 60599:2007 90 % Typical quantities
Gases	2018-10-21 Online data in ppm	2018-11-07 Online data in ppm	2018-12-05 Online data in ppm	2019-01-09 Online data in ppm	2019-02-07 Online data in ppm	
H_2	5	0	0	0	5	60 to 150
O_2	98	98	95	96	99	-
N_2	43488	43509	43490	43502	43508	-
CO	127	128	130	130	133	540 to 900
CO_2	1023	1032	1055	1092	1094	5100 to 13000
CH_4	29	28	30	29	30	40 to 110
C_2H_6	175	178	186	180	185	50 to 90
C_2H_4	0	0	0	0	0	60 to 280
C_2H_2	7	0	0	7	7	3 to 50
TDCG	343	334	346	346	358	< 500

Figure 5.1 below shows the dissolved gas concentration of combustible gases for transformer number 1 in the research site. It can be clearly seen that all the gases are within the required limits, except C_2H_6 which is slightly higher than normal production levels. The limit for C_2H_6 is 90ppm as per IEC 60599:2007, and the highest value recorded is 186ppm.

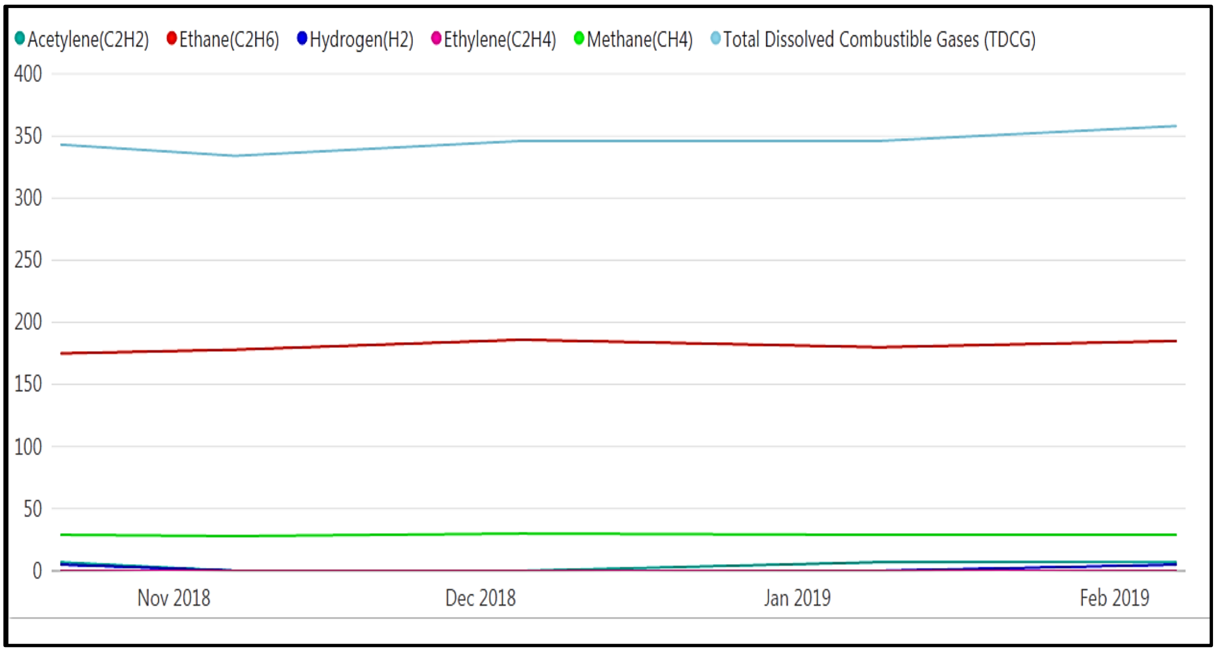


Figure 5.1: KDS transformer 1 Dissolved Gas Concentration

The analysis performed by using the California State University Sacramento (CSUS) method is shown in Table 5.2. It indicates C_2H_6 at 185ppm (>35ppm considered as being abnormal). Thus, C_2H_6 levels are abnormal, whilst other gas levels are normal (see Annexure B - extract CSUS guidelines for combustible gases).

Table 5.2: Transformer 1 results analysis using CSUS Transformers Gas Surveillance Guides

Gas	Results	Normal	Elevated	Abnormal	Analysis
H_2	5	< 150	>150<1000	> 1000	Normal
CH_4	30	< 25	>25<80	> 80	Normal
C_2H_6	185	< 10	>10<34	> 35	Abnormal
C_2H_4	0	< 20	>20<100	> 100	Normal
C_2H_2	7	< 15	>15<70	> 70	Normal
CO	133	< 500	>50<1000	> 1000	Normal

TDCG	358	< 720	>720<5000	> 5000	Normal

The analysis performed by using the California State University Sacramento (CSUS) method is shown in Table 5.2 above. It indicates C_2H_6 at 185ppm (>35ppm considered as being abnormal), whilst other gas levels are normal (see Annexure B - extract CSUS guidelines for combustible gases).

The production rate is expressed as ml/day or ppm/day and was used in the research study to determine the volume of the gases produced per day. The alternative method IEC 60599:2007 typical rates of gas increase for power transformers in ml/day and ppm/day were used for analysis (see extract from IEC 60599:2007 in Annexure C).

The production rate (ml/day) was calculated by using the following formulae:

$$\text{Rate} = [(y^2 - y^1) \text{ x } m] / [\rho \text{ x } (d^2 - d^1)] \qquad (5.1)$$

Where y^1 = reference analysis value
y^2 = last analysis value
m = mass of oil in kg
ρ = density of oil in kg.m^{-3}
d^1 = date for y^1
d^2 = date for y^2

The production rate (ppm/day) was calculated by using the following formulae:

$$\text{Rate} = (y^2 - y^1) / (d^2 - d^1) \qquad (5.2)$$

Where y^1 = reference analysis value
y^2 = last analysis value
d^1 = date for y^1
d^2 = date for y^2

Table 5.3: IEC 60599:2007 typical rates of gas increase for power transformers in ppm/day

Number of days	109	Oil quantity	33509 litres		
Gas	Date 2 07/02/2019	Date 1 21/10/2018	Production ppm/day	Normal ppm/day	Serious ppm/day
H_2	5	5	0	0.149	2.984
CH_4	30	29	0.009	0.075	8.953
C_2H_6	185	175	0.091	0.075	8.953
C_2H_4	0	0	0	0.075	8.953
C_2H_2	7	7	0	0.075	1.492
CO	133	127	0.055	2.984	14.921
CO_2	1094	1023	0.651	8.953	29.843
TDCG	358	343			

The transformer number 1 results were analysed using production rate ppm/day. Table 5.3 above shows the analysis results using IEC 60599:2007 typical rates of gas increase for power transformers in ppm/day. Transformer number 1 dissolved gas analysis results as shown in Table 5.3 indicate that the typical gas increases in ppm/day is normal for all the gases, except Ethane (C_2H_6) gas which has an abnormal value when compared against 60599:2007 typical rates of gas increase for power transformers in ppm/day.

The results for transformer number 1 were also analysed using production rate ml/day. Table 5.4 below contains the analysis results using IEC 60599:2007 typical rates of gas increase for power transformers in ml/day. Transformer number 1 dissolved gas analysis results are provided in Table 5.4. The typical gas increases in ml/day is normal for all the gases, except the Ethane (C_2H_6) gas which has an abnormal value when compared against 60599:2007 typical rates of gas increase for power transformers in ml/day.

Table 5.4: IEC 60599:2007 Typical rates of gas increase for power transformers in ml/day

Number of days	109	Oil quantity	33509 litres	
Gas	Date 2 07/02/2019	Date 1 21/10/2018	Production ml/day	Typical Rates Gas Increase ml/day
H_2	5	5	0	< 5
CH_4	30	29	0.3074	< 2
C_2H_6	185	175	3.074	< 2
C_2H_4	0	0	0	< 2
C_2H_2	7	7	0	< 0.1
CO	133	127	1.845	<50
CO_2	1094	1023	22	< 200
TDCG	358	343		

5.1.2 Dissolved Gas Analysis results of transformer number 3 at KDS

The results history trend of transformer number 3 retrieved for this research study indicates that all the combustible gases are well below the typical rates. Unlike transformer number 1, the production rate of C_2H_6 for transformer number 3 is slightly higher, but within the normal limits (see Table 5.5). The carbon monoxide and carbon dioxide concentrations are both below the typical normal levels.

Table 5.5: Results analysis of DGA transformer 3 at KDS

Gas detected in sample (ppm)						IEC 60599:2007 90 % Typical quantities
Gases	2018-10-02 Online data in ppm	2018-11-30 Online data in ppm	2018-12-09 Online data in ppm	2019-01-12 Online data in ppm	2019-02-04 Online data in ppm	
H_2	5	5	0	0	5	60 to 150

O_2	718	720	725	695	687	-
N_2	24556	27081	26680	24793	27463	-
CO	56	55	56	43	58	540 to 900
CO_2	785	832	835	872	893	5100 to 13000
CH_4	26	26	26	27	29	40 to 110
C_2H_6	68	61	58	66	73	50 to 90
C_2H_4	0	0	0	0	0	60 to 280
C_2H_2	4	0	5	0	4	3 to 50
TDCG	159	147	145	136	169	< 500

Figure 5.2 below shows the graph of dissolved gas concentration of combustible gases for transformer number 3 in the research site. It is evident that all the gases are within the required limits.

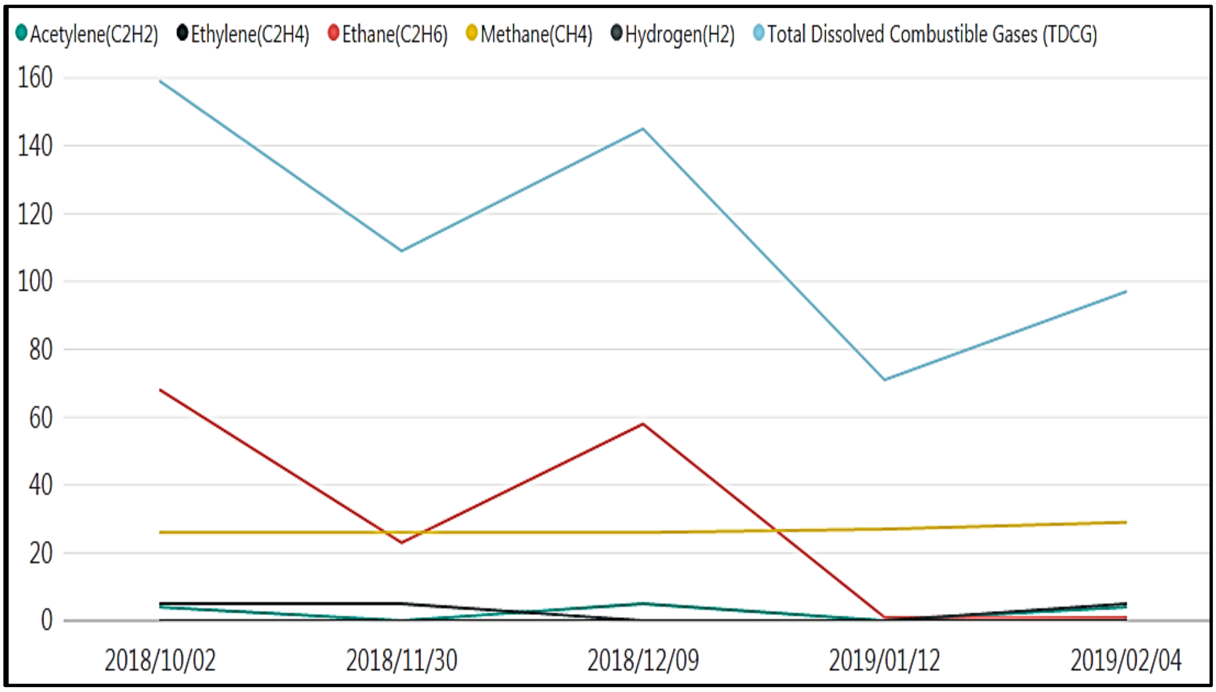


Figure 5.2: KDS transformer 3 Dissolved Gas Concentration

The analysis done by using the California State University Sacramento (CSUS) method (see Table 5.6 below) indicates that all the combustible gases for transformer number 3 are well below the normal levels, except C_2H_6, which is slightly higher than the limits (abnormal). This means that, when using the CSUS method for both transformer number 1 and number 3, C_2H_6 levels were higher than normal production levels.

Table 5.6: Transformer 3 results analysis using CSUS Transformers Gas Surveillance Guides

Gas	Results	Normal	Elevated	Abnormal	Analysis
H_2	5	< 150	>150<1000	> 1000	Normal
CH_4	29	< 25	>25<80	> 80	Normal
C_2H_6	73	< 10	>10<34	> 35	Abnormal
C_2H_4	0	< 20	>20<100	> 100	Normal
C_2H_2	4	< 15	>15<70	> 70	Normal
CO	58	< 500	>50<1000	> 1000	Normal
TDCG	169	< 720	>720<5000	> 5000	Normal

The production rate is expressed as ml/day or ppm/day and was used in the research study to determine the volume of the gases produced per day. Refer to Table 5.7 and 5.8 below for the production rate calculations methods that were used. The formulas are exactly the same as the ones used for transformer number 1.

Table 5.7: IEC 60599:2007 typical rates of gas increase for power transformers in ppm/day

Number of days	**124**	**Oil quantity**	**33509 litres**		
Gas	Date 2 04/02/2019	Date 1 02/10/2018	Production ppm/day	Normal ppm/day	Serious ppm/day
H_2	5	5	0	0.149	2.984

CH_4	29	26	0.024	0.075	8.953
C_2H_6	73	68	0.040	0.075	8.953
C_2H_4	0	0	0	0.075	8.953
C_2H_2	4	4	0	0.075	1.492
CO	58	56	0.016	2.984	14.921
CO_2	893	785	0.871	8.953	29.843
TDCG	169	159			

Transformer number 3 results were analysed using production rate ppm/day. Table 5.7 above shows the analysis results using IEC 60599:2007 typical rates of gas increase for power transformers in ppm/day. Transformer number 3 dissolved gas analysis results as shown in Table 5.7 reveal that the typical gas increases in ppm/day is normal for all the gases. No deviations were discovered in the transformer.

Table 5.8: IEC 60599:2007 typical rates of gas increase for power transformers in ml/day

Number of days	124	Oil quantity	33509 litres	
Gas	Date 2 04/02/2019	Date 1 02/10/2018	Production ml/day	Typical Rates Gas Increase ml/day
H_2	5	5	0	< 5
CH_4	29	26	0.810	< 2
C_2H_6	73	68	1.351	< 2
C_2H_4	0	0	0	< 2
C_2H_2	4	4	0	< 0.1
CO	58	56	0.540	<50
CO_2	893	785	29	< 200

TDCG	169	159		

Transformer number 3 results were analysed using production rate ml/day. Table 5.8 above shows the analysis results using IEC 60599:2007 typical rates of gas increase for power transformers in ml/day. The transformer number 3 dissolved gas analysis results as contained in Table 5.8 indicate that the typical gas increases in ml/day is normal for all the gases. No deviations were recorded in the transformer.

5.1.3 Incompatible contaminants evaluated on the research transformers

5.1.3.1 Red oxide paint in transformer radiators

The transformer radiators form a critical part of the cooling system of a transformer; thus, the oil is permanently in contact with the inner surface of the radiators. The final steps of manufacturing radiators entails that paint (red oxide) is flushed through the radiator. This is done for two main reasons. The first reason is to entrap any loose debris that might be left after the manufacturing of the radiators, and the second reason being to cover any bare metal that is exposed within the inside surface, for example to prevent rust.

After the paint is drained through natural gravity, hot air is passed through the radiator to cure the paint. It is then sealed prior to storage or transport. It has been established in experimental analysis at the oil laboratory that uncured paint will cause unnatural gassing when in contact with transformer oil. Elevated levels of Ethane, Carbon Dioxide Methane and Hydrogen have been observed. Table 5.9 below show the results for the oil compatibility test performed on uncured red oxide paint.

Table 5.9: Table with results for oil compatibility test performed on uncured red oxide paint

Gas	KDS transformer 1 oil analysis in ppm	Uncured red oxide paint oil sample in ppm
H_2	11	218
O_2	2491	20323
N_2	45053	139767
CH_4	43	147
CO	141	213
CO_2	1164	1732
C_2H_2	0	0
C_2H_4	15	17
C_2H_6	122	238

It can be clearly seen in Table 5.9 above that the uncured paint does have a negative impact on the gassing of the oil, and that it is not compatible with the insulating oil. Transformer number 1 is having abnormal levels of Ethane gas, and transformer number 3 is having slightly high level of Ethane gas, but within the limits as compared to IEC standards and other diagnostic methods. The gassing patterns found in these transformers compare to the experimental data obtained from the compatibility tests that were performed in the laboratory [41].

The origin of the high levels of ethane can be directly connected to the painting of the radiators. The introduction of transformer online condition monitoring technology for this research was successful. The technology was able to assist in predicting a fault on the transformer. Furthermore, the short message system was used via this technology to send notifications of any abnormal levels of ethane gas in the transformers.

5.1.4 Temperature, load and ageing monitoring results analysis

5.1.4.1 Transformer number 1 temperature profiles and current results

The data of transformer number 1 at KDS were analysed to predict power transformer failure in this research study. The top oil temperature, winding hot spot temperature, ambient temperature and loading (current) results of transformer number 1 at KDS will be analysed in this section. The analysis will only focus on the days where the highest ambient temperature was recorded. The analysis will be conducted in the values recorded on 23 January 2019. A record high of 44°C ambient temperature was recorded at KDS.

These extreme temperatures coincided with the heat wave the country experienced in January 2019. This will also show the impact the heat wave is having on the health of power transformers.

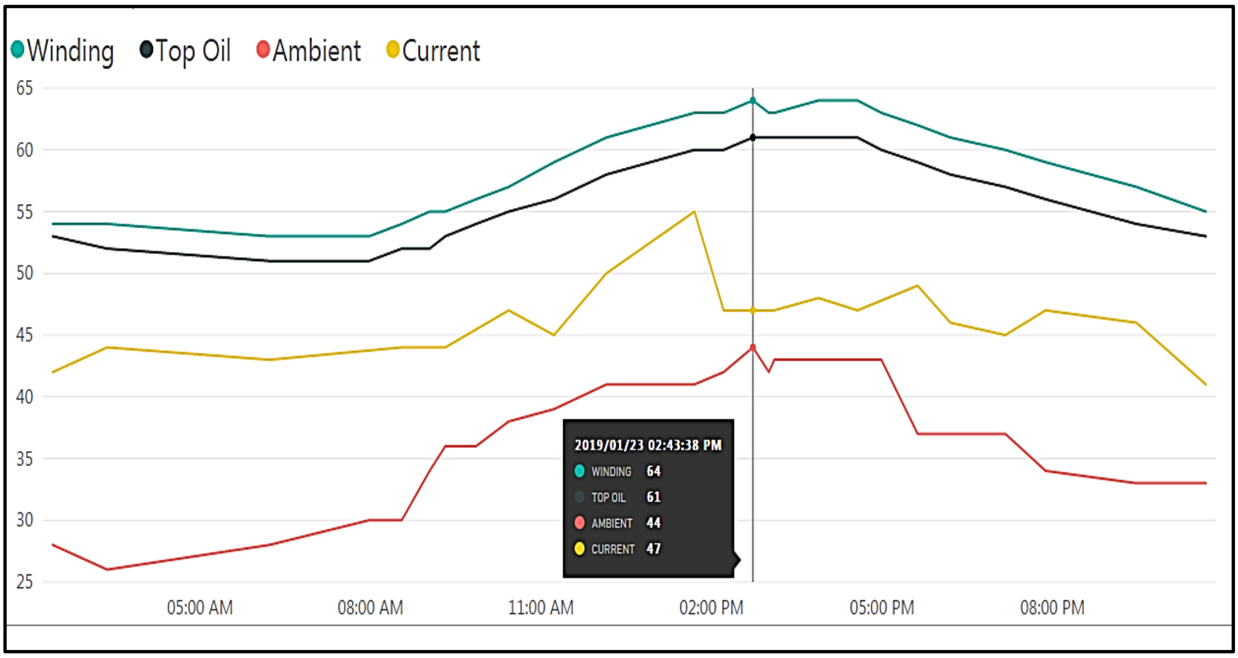


Figure 5.3: Temperature results and current of transformer number 1 at KDS

It can be clearly seen in Figure 5.3 (transformer number 1) above that there is a positive correlation between the three temperatures (ambient, winding and top oil) and current. The vertical line in the graph shows that on the 23 January 2019 at 02:43 PM, when ambient temperature increased, the winding temperature and top oil temperature also increased, but the current remained constant without increasing.

The current remained constant while the ambient, top oil and winding temperatures increased. It is very important to highlight that not only loading on the transformer can affect its lifespan, but it is crucial to consider the ambient temperature when designing the transformer to avoid failures, since the ambient temperatures in hot areas such as the Northern Cape have a serious impact on the lifespan of a transformer.

5.1.4.2 Transformer number 3 temperature profiles and current results analysis

The analysis will only focus on the days where the highest ambient was recorded. The analysis will be conducted in the values recorded on 23 January 2019 at 03:13 PM. A high ambient temperature of 42°C was recorded at KDS in that afternoon. These extreme temperatures coincided with the heat wave the country experienced in January 2019. This will also show the impact of such a heat wave on the health of power transformers.

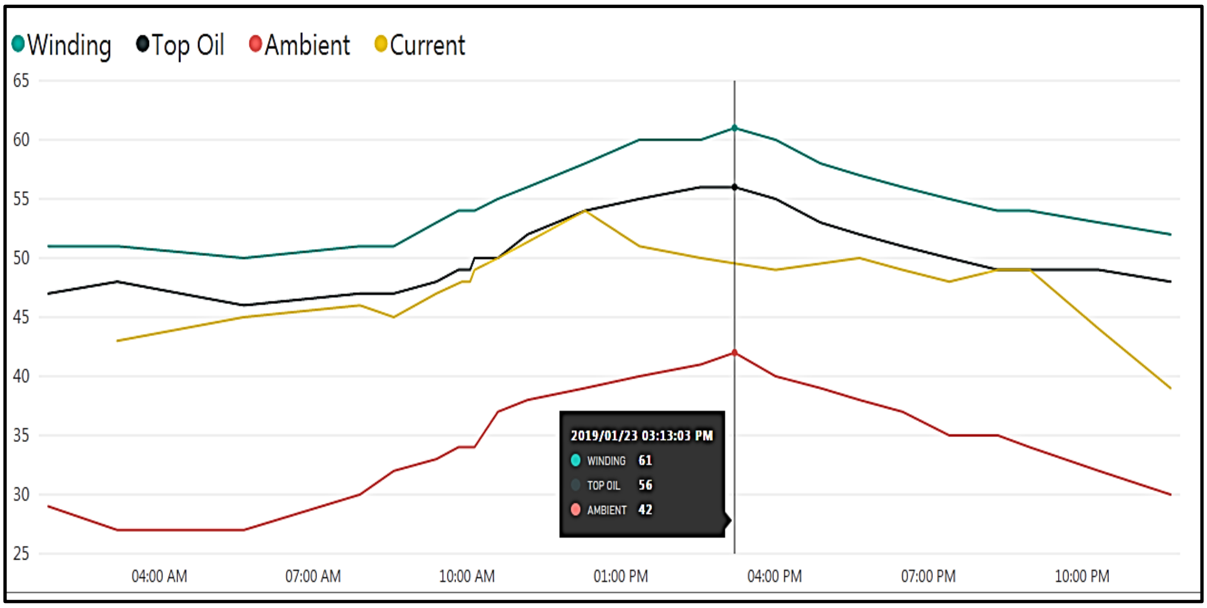


Figure 5.4: Temperature results and current of transformer number 3 at KDS

It can be clearly seen in Figure 5.4 (transformer number 3) above that there is a positive correlation between the three temperatures (ambient, winding and top oil) and current. The vertical line in the graph shows that on the 23 January 2019 at 03:13 PM, when ambient temperature increased, the winding temperature and top oil temperature also increased, but the current remained constant without increasing.

The current remained constant while the ambient, top oil and winding temperatures increased. It is very important to highlight that not only loading on the transformer can affect its lifespan, but also ambient temperatures. Hence, when designing the transformer, ambient temperatures need to be taken into account, as these temperatures in the hot areas such as the Northern Cape have a serious impact on the lifespan of a transformer.

As can be seen in Figure 5.3 and Figure 5.4, the ambient temperature has an effect in increasing the hot-spot temperature above the rating of the paper, without overloading the transformer. This may result in the failure of transformer insulation due to the extreme increase in the ambient temperature.

5.1.5 Bushing condition monitoring results analysis

5.1.5.1 Transformer number 1 dissipation factor (Tan Delta) and capacitance results analysis

The online measurements of capacitance results will be analysed in this section. Figure 5.5 below shows the averaged dissipation factor of the three phases (red, white and blue) bushings on the primary side of transformer number 1 at KDS.

The type of bushings fitted on transformer number 1 and 3 for this research study are called Resin Impregnated Bushings (RIP).

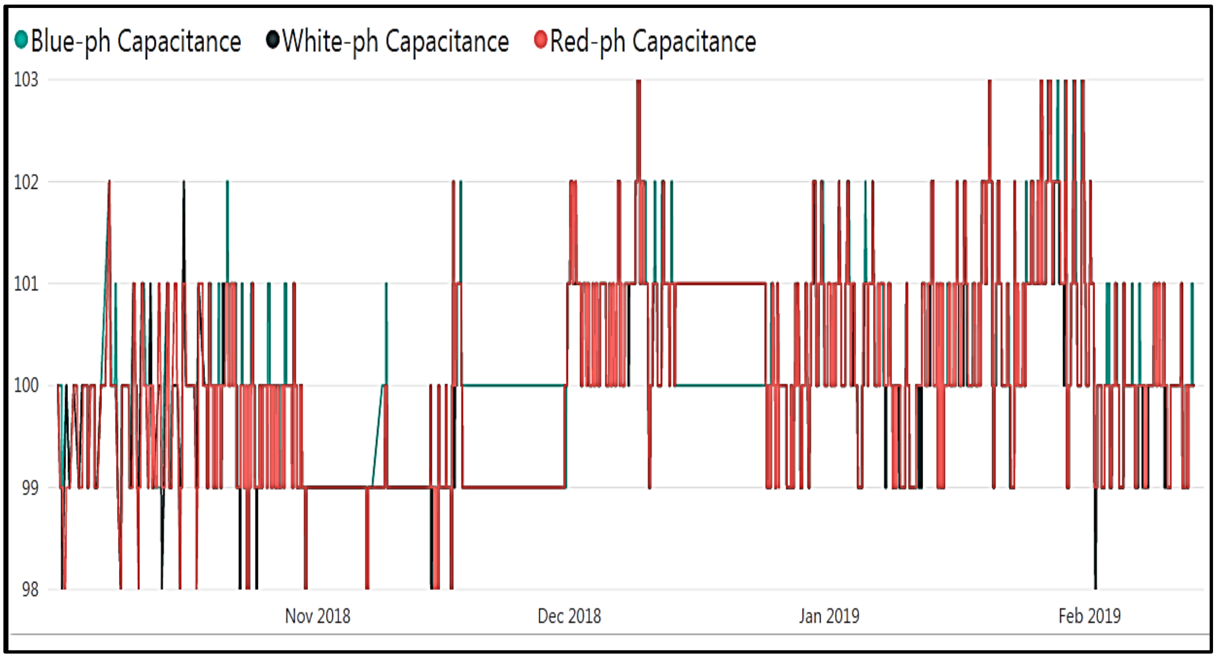


Figure 5.5: Capacitance results of transformer number 1 bushings at KDS

The highest capacitance values measured on all three phases is 103%, whilst the lowest capacitance values measured in all three phases is 98%. The highest and the lowest figures were measured during the bushing operation in the past four months. It can also be seen in Figure 5.5 above that there is a slight change in capacitance for all three phases (red, white and blue), but within the acceptable limits.

According to IEEE C57.19.01, the acceptable change in capacitance (%) for RIP transformer bushings is ± 10%. The results indicate that there were no partial breakdowns, voids and cracks on all three bushings.

Figure 5.6 below shows the measured averaged dissipation factor three phases (red, white and blue) bushings in the primary side of transformer number 1 at KDS.

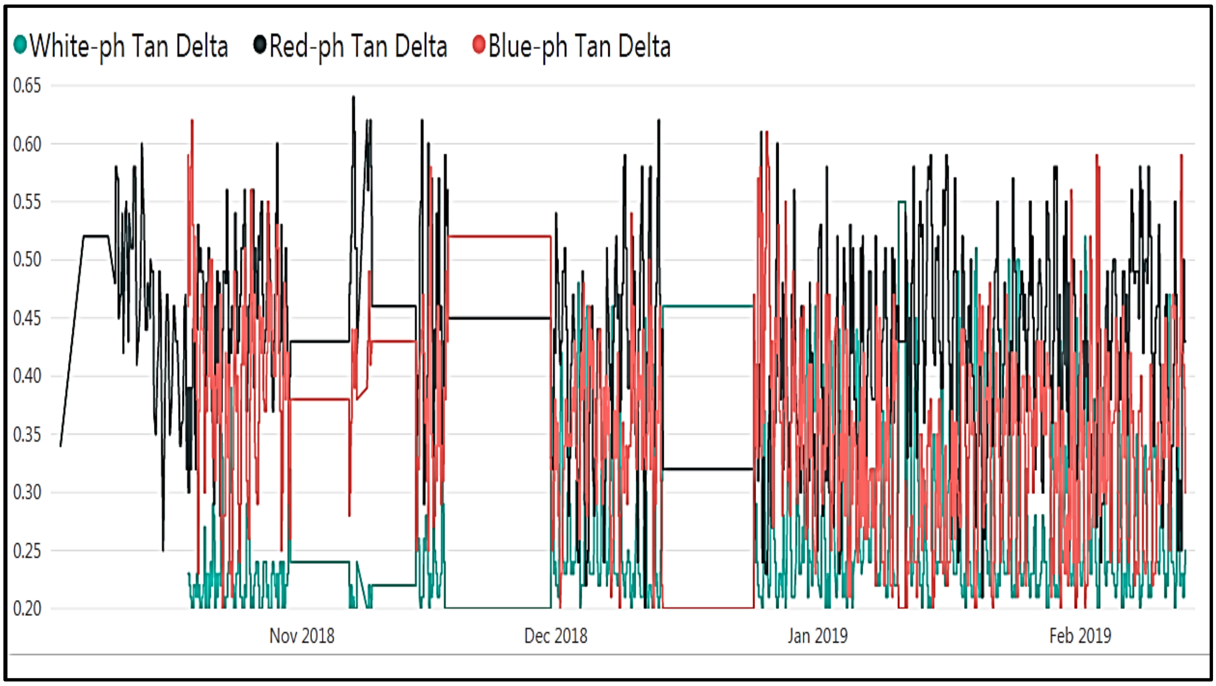


Figure 5.6: Dissipation factor results of transformer number 1 bushings at KDS

The highest Tan Delta values measured on all three phases is 0.63%, and the lowest capacitance values measured on all three phases is 0.20%. The highest and the lowest figures were measured during the bushing operation during the past four months. It can also be seen in Figure 5.6 above that there is a slight change in Tan Delta values for all three phases (red, white and blue), but within the acceptable limits.

The dissipation factor of all three bushings on the primary side of the transformer are regulating beyond the limit of 0.85 %. According to IEEE C57.19.01, the power factor limit for RIP transformer bushings is 0.85 %. The results for three bushings mean that there is no ageing and no insulation breakdown in the bushings.

5.1.5.2 Transformer number 1 bushings phase voltage results analysis

The higher the voltage levels, the higher the risk of bushing failures. The data are analysed, and a recommendation is made based on the results of the phase voltages. Figure 5.7 below shows the averaged phase voltage of three bushings (red, white and blue) on the primary side of transformer number 1 at KDS.

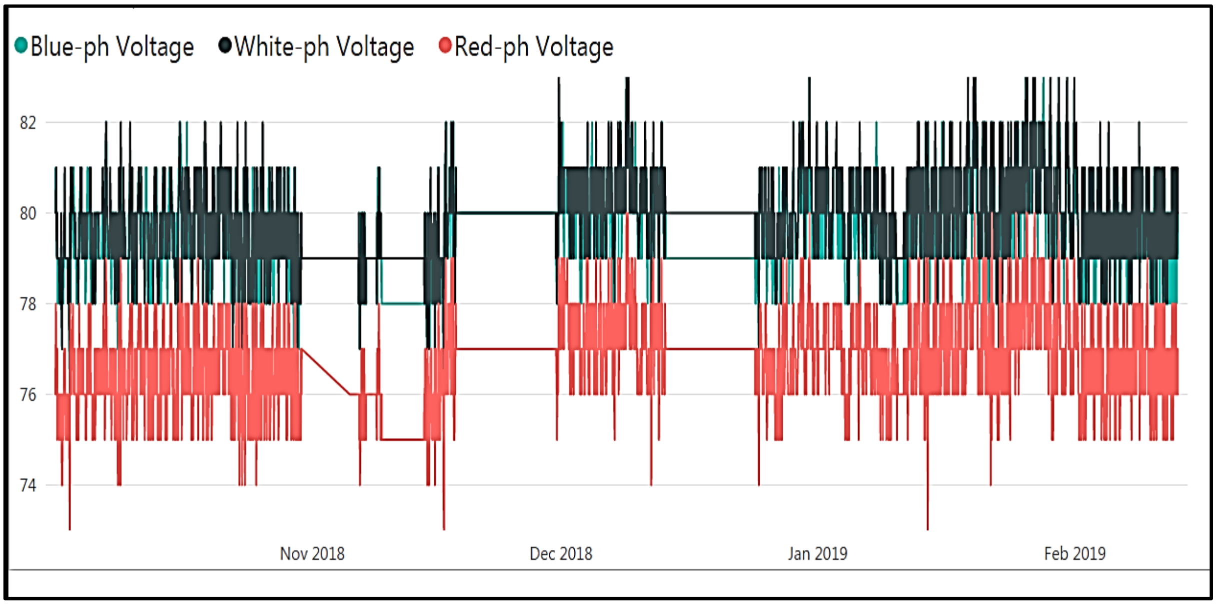


Figure 5.7: Phase voltage results of three bushings in the primary site of transformer 1

The phase voltage on all three bushings is 76.2kV, the upper limit voltage is 83.3kV, and the lower limit voltage is 68.58kV. The limits are calculated based on the NRS 048-2:2015 voltage regulation lower and upper limits of ±5%. The highest values of phase voltages recorded on 31 January 2019 at 10:23 PM were 83kV for both blue phase and white phase bushings. The lowest value recorded was 73kV for red phase bushing on 08 December 2018 at 06:04 AM.

As shown in Figure 5.7 above, the red phase voltage was regulating within the voltage regulation lower and upper limits of ±5%. The white and blue phases were in some instances regulating slightly closer to the upper limit of +5%. This is not a major cause of concern, as these occurrences were not constant but only occasional.

5.1.5.3 Transformer number 3 dissipation factor (Tan Delta) and capacitance results analysis

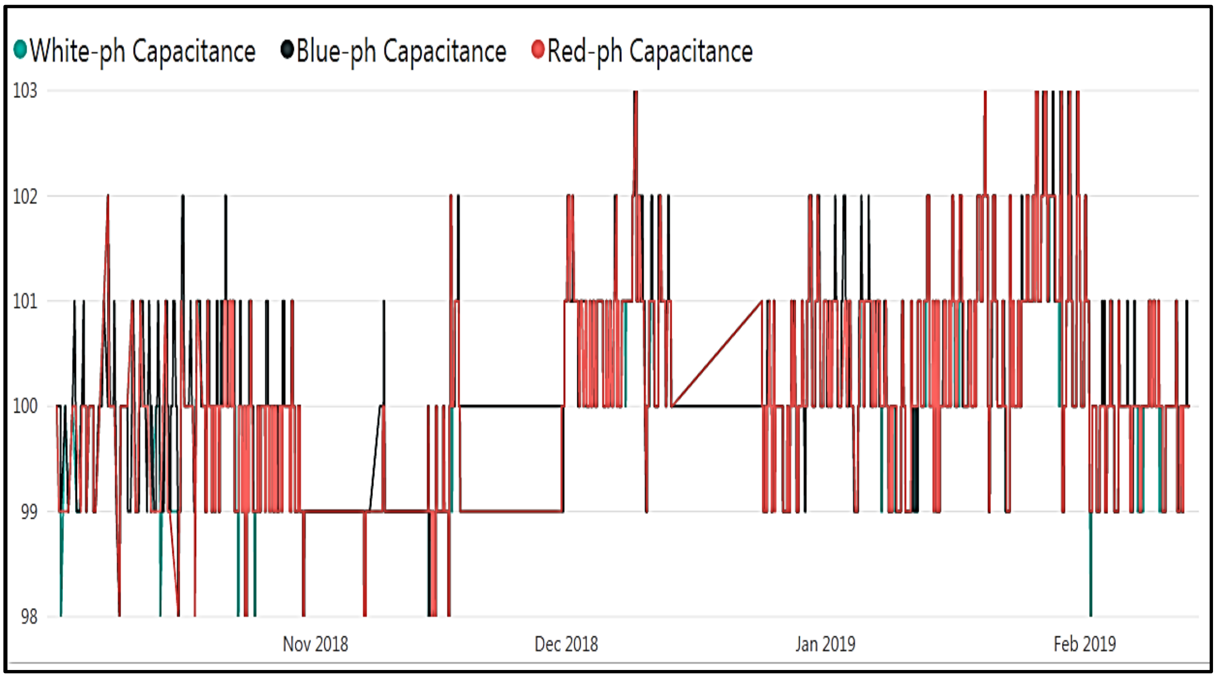


Figure 5.8: Capacitance results of transformer number 3 bushings at KDS

Similar to transformer number 1, the highest capacitance values measured on all three phases is 103%, whilst the lowest capacitance values measured on all three phases is 98%. The highest and the lowest figures were measured during the bushing operation during the past four months. It can also be seen in Figure 5.8 above that there is a slight change in capacitance for all three phases (red, white and blue), but within the acceptable limits.

According to IEEE C57.19.01, the acceptable change in capacitance (%) for RIP transformer bushings is ± 10%. The results reveal that there were no partial breakdowns, voids and cracks in the three bushings.

Figure 5.9 below shows the measured averaged dissipation factor three phases (red, white and blue) bushings in the primary side of transformer number 3 at KDS.

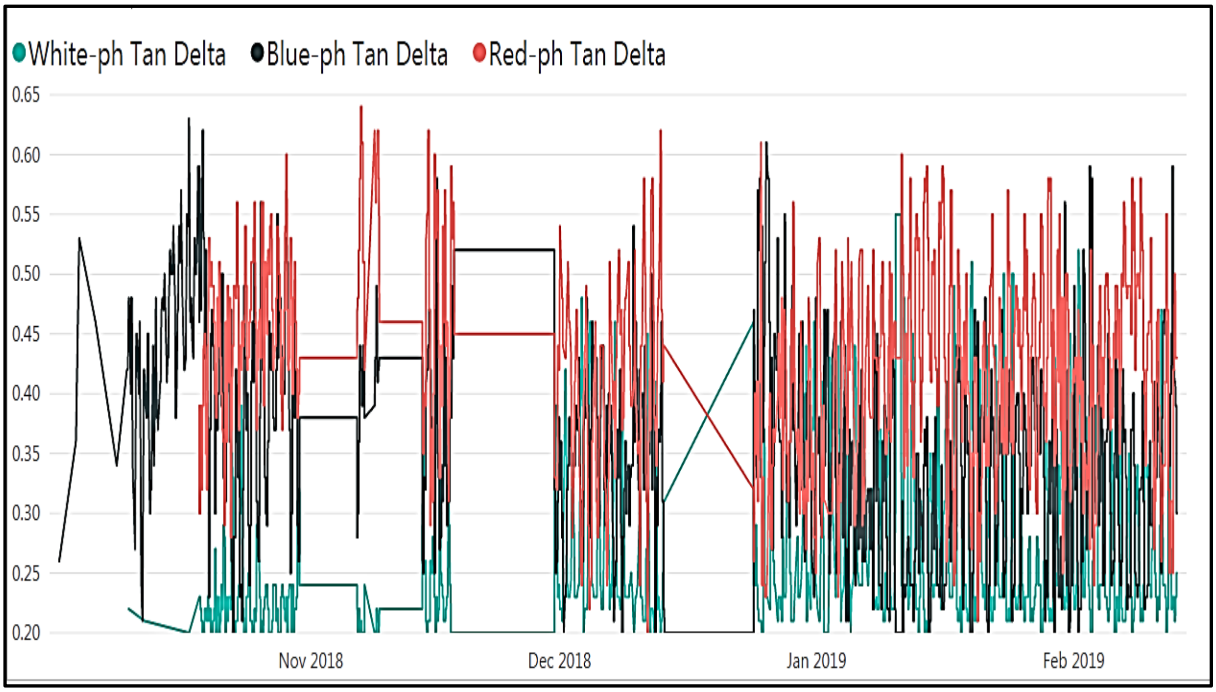


Figure 5.9: Dissipation factor results of transformer number 1 bushings at KDS

The highest Tan Delta values measured in all three phases is 0.64%, and the lowest capacitance values measured in all three phases is 0.20%. The highest and the lowest figures were measured during the bushing operation in the last four months of the empirical study. It can also be seen in Figure 5.6 above that there is a slight change in Tan Delta values for all three phases (red, white and blue), but within the acceptable limits.

The dissipation factor of all three bushings on the primary side of the transformer are regulating beyond the limit of 0.85 %. According to IEEE C57.19.01, the power factor limit for RIP transformer bushings is 0.85 %. The results of three bushings indicate that there are no ageing and insulation breakdown on the bushings.

5.1.5.4 Transformer number 1 bushings phase voltage results analysis

Figure 5.10 below shows the averaged phase voltage results of three bushings (red, white and blue) in the primary side of transformer number 3 at KDS.

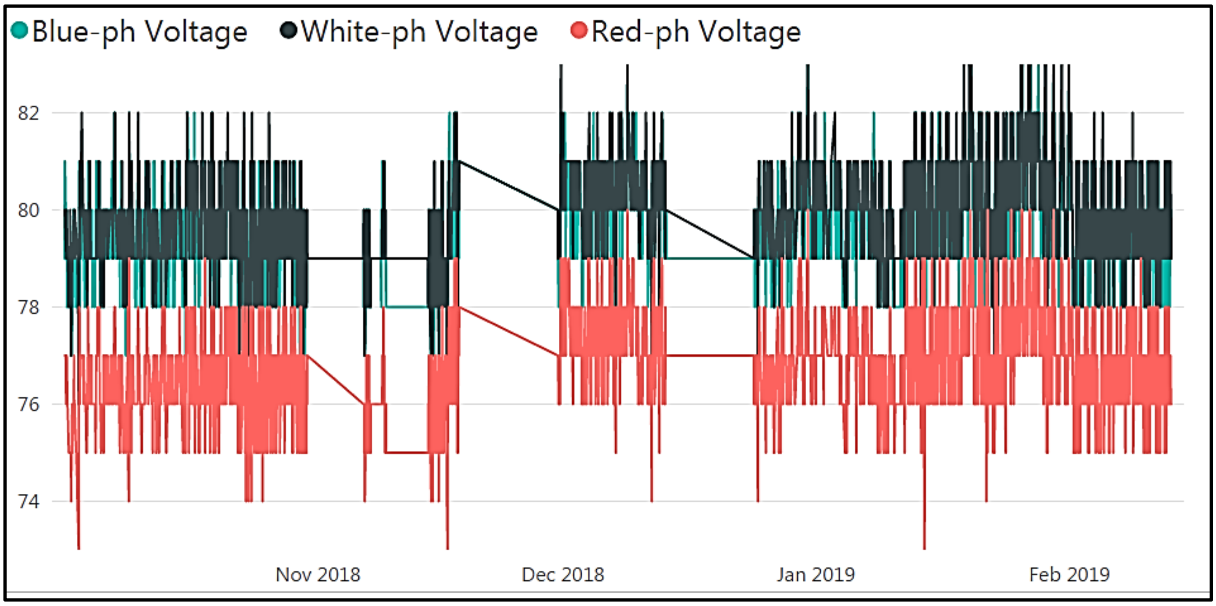


Figure 5.10: Phase voltage results of three bushings in the primary site of transformer 3

The phase voltage on all three bushings is 76.2kV, the upper limit voltage is 83.3kV and the lower limit voltage is 68.58kV. The limits are calculated based on the NRS 048-2:2015 voltage regulation lower and upper limits of ±5%.

The highest values of phase voltages recorded were 83kV for both blue phase and white phase bushings on the 30th of December 2019 at 11:15 PM. The lowest value recorded was 73kV for red phase bushing on the 14th of January 2019 at 06:04 AM.

As shown in Figure 5.10 above, the red phase voltage were regulating within the voltage regulation lower and upper limits of ±5%. The white and blue phases were regulating slightly close to the upper limit of +5% sometimes, but this is not a major problem, as it only occurred occasionally.

5.1.6 Cooling fans monitoring results analysis

Figure 5.11 below shows that fan 1 and fan 2 of transformer number 1 operated correctly when the winding temperature and ambient temperature increased. Most of the time fan 1 and fan 2 operated at the same time, and fan 3 never operated during the chosen period (1 January 2019 to 31 January 2019). The reason to select the month of January 2019 is that it is the hottest month in the Northern Cape area. A heat wave was recorded, and loading started to peak during January following the festive season holidays.

It can be further seen in Figure 5.11 below that during periods of low load or low ambient temperature, the fans were not running. During the periods of high loading or high ambient temperature, fans were normally activated and were drawing a current between 3A and 4A to provide extra cooling on the transformer. The measurement of fans current in the research study was necessary to verify the correct operation of each fan.

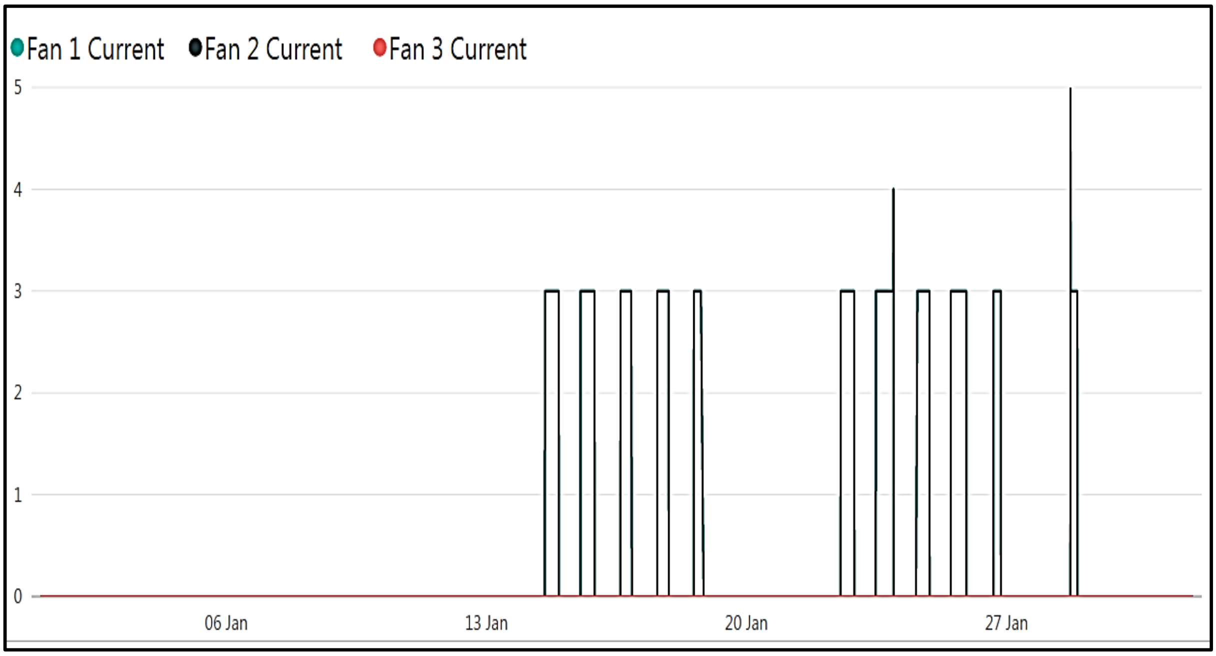


Figure 5.11: Fan current results of transformer number 1 at KDS

Figure 5.11 above shows that fan 1 and fan 2 of transformer number 1 operated correctly when the winding temperature and ambient temperature increased. Fan 1 and fan 2 mostly operated at the same time, whilst fan 3 never operated during the chosen period (1 January 2019 to 31 January 2019). The reason for selecting the month of January 2019 is because it was the hottest month as a result of a heat wave that was recorded during this month. Furthermore, loading started to peak during January 2019 following the festive season holidays.

It can be further seen in Figure 5.11 above that during periods of low load or low ambient temperature, the fans were not running. During periods of high loading or high ambient temperature, fans were normally activated and were drawing a current between 3A, 4A and

5A to provide extra cooling on the transformer. The measurement of fans current in the research study was necessary to verify the correct operation of each fan.

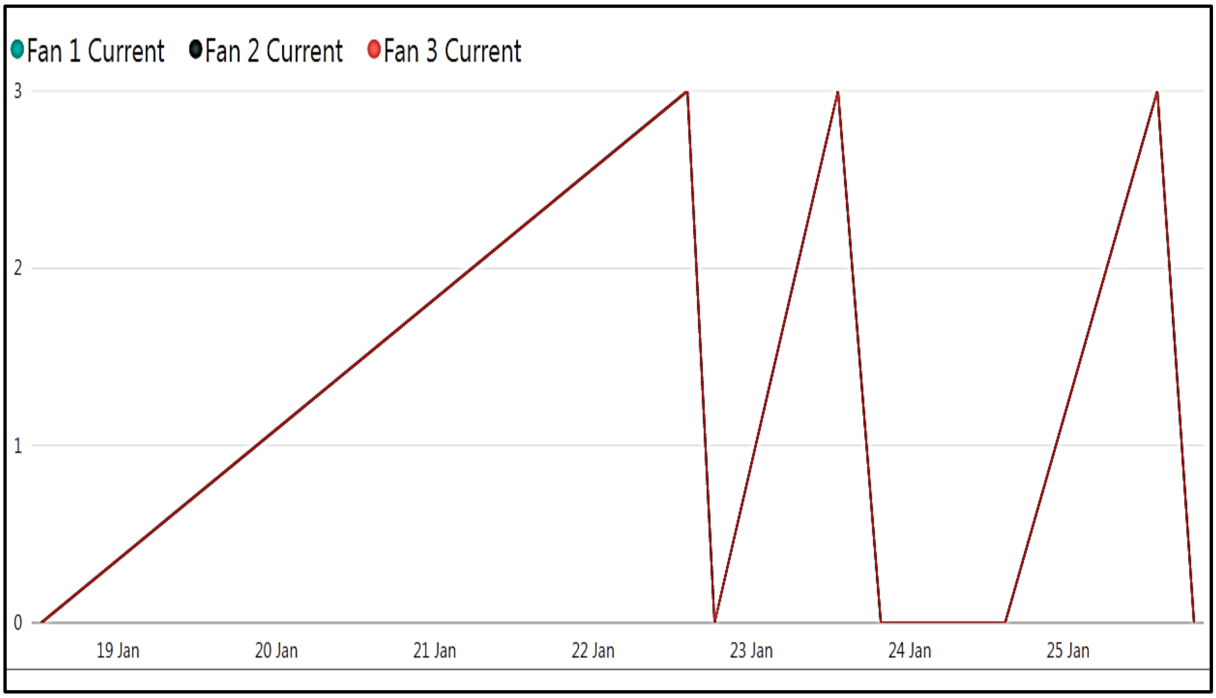


Figure 5.12: Fan current results of transformer number 3 at KDS

Figure 5.12 above shows fan 1, fan 2 and fan 3 of transformer number 3 operated correctly when the winding temperature and ambient temperature increased, compared to transformer number 1, where fan 3 never operated. It was different for transformer number 3, as all three fans operated during the chosen period (1 January 2019 to 31 January 2019). As already indicated, the month of January was selected, as it was the hottest month due to a heat wave in the Northern Cape, and loading started to increase in January 2019 following the festive season holidays.

It can also be seen in Figure 5.12 above that fan 1, fan 2 and fan 3 mostly operated simultaneously. It is important to highlight that at some point in transformer number 3, fan 1 operated alone for certain periods, as compared to transformer number 1, where fan 1 and 2 operated at the same time. It can further be seen that during periods of low load or low ambient temperature, the fans were not operational, and transformer number 3 fans operated fewer times than transformer number 1 fans. The current of 3A was drawn by fan 1 and fan 2 during operation.

The results show that the fans were operating on a regular basis to cool the two transformers when required. The Oil Natural Air Natural (ONAN) cooling method will not be adequate in hot areas because of the high ambient temperatures associated with these areas most of the time, and thus the forced air-cooling method will be more appropriate. It became evident from this research study that it is critical to ensure that the transformer fans are operating as they should, and hence their effective operation should be closely monitored.

5.1.7 On-load tap changer condition monitoring results analysis

Figure 5.13 below shows the results analysis of transformer number 1 operations on the research site. The online condition monitoring technology indicated that the tap changer of transformer number 1 has operated 32 times over the past three months.

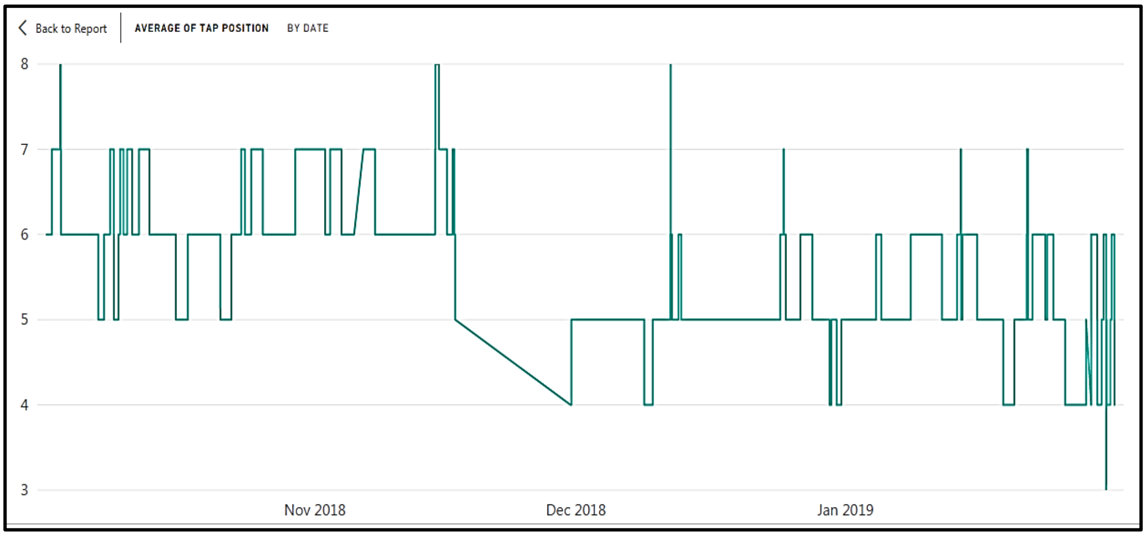


Figure 5.13 Tap changer results of transformer number 1 at KDS

The results in Figure 5.13 above shows that the tap changer operated between tap 3 and tap 8 positions most of the time on transformer number 1 at KDS. The system high voltage of the transformer is 132kV, the upper limit voltage is 138.6kV and the lower limit voltage is 125.4kV. The limits are calculated based on the NRS 048-2:2015 voltage regulation lower and upper limits of ±5%.

The name plate of transformer number 1 and number 3 on the research site was used as a reference point to quantify the tap positions versus the system voltages. It was discovered from the name plate (see annexure D) that the system voltage of tap position 3 is 135,5kV, and the system voltage of tap 8 is 127kV. It is important to note that between tap 3 and tap 8 positions there is compliance with the NRS 048-2:2015 voltage regulation lower and upper limits.

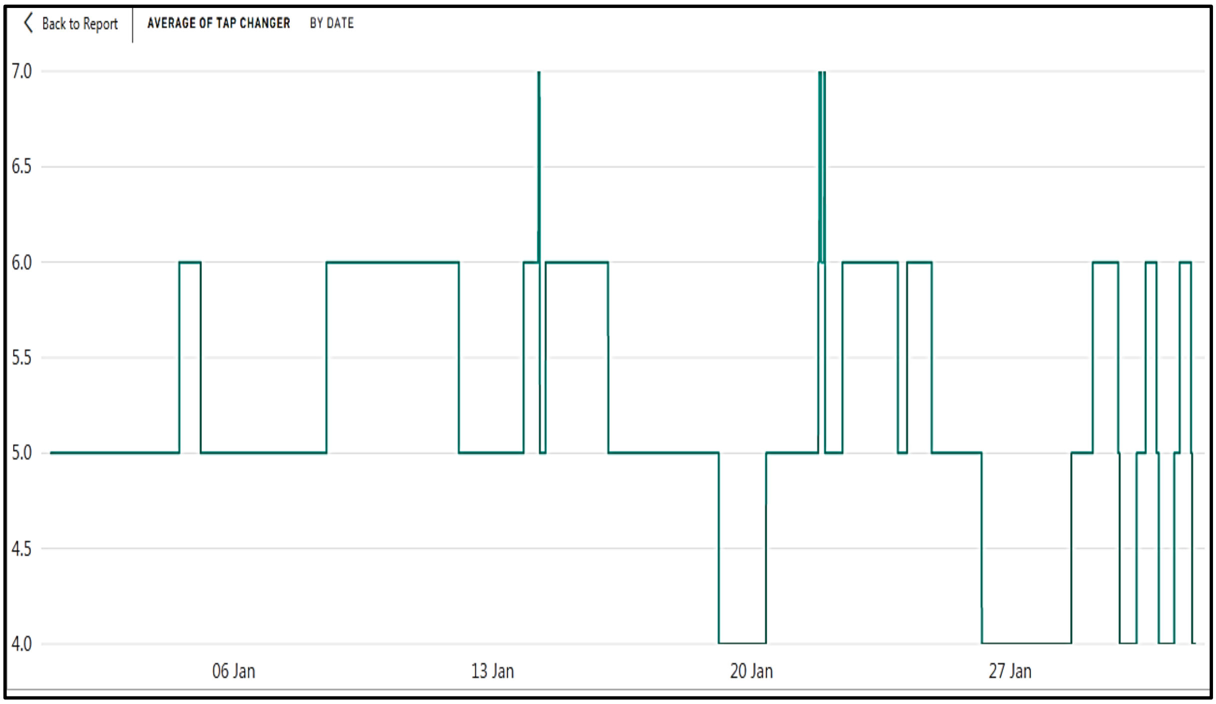


Figure 5.14 Tap changer results of transformer number 3 at KDS

The results in Figure 5.14 above reveal that the tap changer operated between tap 3 and tap 8 positions most of the time on transformer number 3 at KDS. The system voltages and the NRS voltage limits are the same as for transformer number 1. The limits are calculated based on the NRS 048-2:2015 voltage regulation lower and upper limits of ±5%. The name plate of transformer number 3 on the research site was used as a reference point to quantify the tap positions versus the system voltages.

It was discovered from the name plate (see Annexure B) that the system voltage of tap position 4 is 133,7kV and the system voltage of tap 8 is 127kV. As already mentioned, there is compliance with the NRS 048-2:2015 voltage regulation lower and upper limits between tap 4 and tap 8.

5.2 Conclusion

In this chapter, it was clearly indicated how historical data are retrieved from the transformer via online monitoring, and how data were utilised to trend results, and to establish the possible failure or major faults on power transformers. Thus, online condition monitoring of transformers can be used by the sectors such as municipalities and electrical utility companies to monitor the asset health of their power transformers.

It can be seen from the discussion of different results parameters that the use of an online transformer monitoring system has proven to be effective in assisting with data generation to detect major faults on power transformers. Power transformer failure is usually considered as a major cause for unplanned outage. Ensuring good condition of high-voltage bushings, tap changers, active parts, effective cooling and temperatures within the norm are of vital importance for maintaining power supply reliability. However, some industry statistics show that 80% of equipment failure incidents happened randomly and could not be detected during common testing and maintenance. It has been observed that most of the utilities sample the oil from power transformers at least once a year. The risk with annual routine oil sampling is that prior to routine sampling the engineers are relying on the previous year's results. Much can happen in a period of one year in as far as the health of the power transformer is concerned, and whilst the team is waiting to sample for the next financial year. From the transformer diagnostic online condition monitoring used, it became evident that such monitoring provides data measurements by oil sampling 24 hours a day.

It has been established in experimental analysis at the oil laboratory that uncured paint will cause unnatural gassing when in contact with transformer oil. Elevated levels of Ethane, Carbon Dioxide, Methane and Hydrogen have been observed (see Table 5.9). The origin of the high levels of Ethane can be directly connected to the painting of radiators.

It was noticed that the ambient temperature has an effect on increasing the hot spot temperature above the rating of the paper, without overloading the transformer. This may result in the premature failure of transformer insulation due to the extreme increase in the ambient temperature. It has also been found that most of the utilities are covering only the testing of dissipation factor (Tan Delta) and capacitance in the bushings, excluding phase voltages on the high voltage side. Bushing Tan Delta tests are synchronised with the tap changer maintenance.

The dissipation factor tests are done once in six years on the bushings. It was discovered that the biggest disadvantage of this maintenance strategy is the unknown condition of the bushing until the maintenance period arrives, and also that power to customers is switched off when bushing Tan Delta tests on transformers are conducted, as an outage is needed.

The maintenance strategy of the utilities ignores the importance of monitoring the cooling fans on the transformers. If the cooling fans are not working correctly due to any unforeseen reason, this type of fault will not be detected. Furthermore, if the cooling fans are not working correctly, it significantly impacts on the transformer's lifespan and ability to be loaded.

CHAPTER 6: CONCLUSION AND RECOMMENDED FURTHER STUDIES

6.1 Conclusion

This chapter provides conclusions on online condition monitoring technology, which entails continuously monitoring the condition of the transformer bushings, tap changer, cooling fans, insulating oil and winding temperature; and giving warnings signs and trigger alarms should any of the parameters exceed the set limits. This prompts preventative action to be taken before a transformer fails. The use of a transformer online monitoring system has proven to be effective in assisting with generating data to detect major faults in power transformers. Power transformer failure is usually considered as a major cause for unplanned outage. Ensuring that high-voltage bushings, tap changers and active parts are in a good condition; that temperatures are within the acceptable norm, and that adequate cooling takes place, are of vital importance to maintain power supply reliability, as presented in Chapter 2. The emphasis was on the installed base of power transformers, failure rate and failure modes. This chapter exposed that there is a need to introduce this technology in South Africa based on the catastrophic failures of power transformers recorded, which sometimes even result in catastrophic fires.

In Chapter 3, the online condition monitoring technology was introduced and installed in order to demonstrate the potential benefits to be gained at the research study site when using the technology to assist in predicting the potential failure of power transformers. The cost analysis was performed over a period of ten years, as compared to the current costs of maintenance/monitoring and asset replacement strategies. The total saving per year was a great benefit for tasks such as inspections, maintenance, monitoring and asset replacement to be performed.

In Chapter 4, the results from the data retrieved in the server were discussed. The results of each transformer parameter monitored by online condition monitoring technology installed in the research site were provided. The DGA diagnostic method was used to predict the faults in power transformers in the research site. The results from the bushings, cooling fans, tap changer and temperatures were also discussed in this chapter.

In Chapter 5, the results analysis of online condition monitoring transformer parameters was discussed in detail. The introduction of online condition monitoring in power transformers can also be used to:

- sample and analyse the oil samples and provide data measurements of oil sampling 24 hours a day;
- analyse the relationship between the ambient temperature, winding temperature, top oil temperature and loading in power transformers;
- find the importance of providing the measurements of dissipation factor (Tan delta), capacitance and the phase voltages of the bushings in the high voltage side of the transformer 24 hours a day;
- derive the best maintenance strategy for the utilities regarding the monitoring of the cooling fans on the transformers; and
- detect the negative impact of uncured paint on the gassing of the oil in the power transformers.

6.2 Suggestions for further studies

The study has revealed the following areas that could be looked into during further studies on this research area:

- Partial discharge monitoring can be installed and integrated with the existing online condition monitoring to analyse insulation breakdowns in the bushings and the windings of power transformers.
- More work needs to be done in integrating the furanic testing with online condition monitoring to be able to measure the transformer insulation paper degradation online.
- A study based on the usage of unmanned aerial vehicle to conduct substation monthly visual inspections and infrared scanning of power transformers.
- Since servers for data storage are delivered with MODBUS communication protocol output as standard, the new technology should be investigated to convert MODBUS communication protocol into DNP3 communication protocol, to enable the SCADA to communicate clearly with the server.
- More work needs to be done in intregarting the cyber security principles in the operational technology environment with transformer online condition monitoring for stricter access control of external information.

6.3 Conclusion

In the final analysis, the importance of transformer online monitoring was pointed out, and how data were utilised to trend results and establish the possible failure or major faults on power transformers. Transformer online condition monitoring can be used by sectors such as municipalities and electrical utility companies to monitor the asset health of their power transformers. The use of a transformer online monitoring system has proven to be effective in assisting with the generation of data to detect major faults on power transformers. Power transformer failure is usually considered as a major cause for unplanned outage. The system's reliability to keep the supply of electricity ongoing will be enhanced, and there will be a reduction in maintenance costs as a result of using the online monitoring technology. Having a stable, sufficient supply of electricity will enable South Africa to grow into the largest and most developed economy in Africa.

6.4 Research Output

During the course of this research work, the following papers were accepted and presented:

- **T.A Motau,** H.J. Vermaak, "Utilizing on-line gas analyser to detect gassing transformer in a distribution substation", SAUPEC conference, 31 January 2017**.**

- **T.A Motau,** H.J. Vermaak, "Optimisation of on-line bushing monitoring system to predict power transformer bushing failures in distribution networks", SAUPEC conference, 24 January 2018**.**

APPENDICES

Annexure A: Extract from IEC 60599:2007 for Typical Dissolved Gas Concentration Levels in Power Transformers

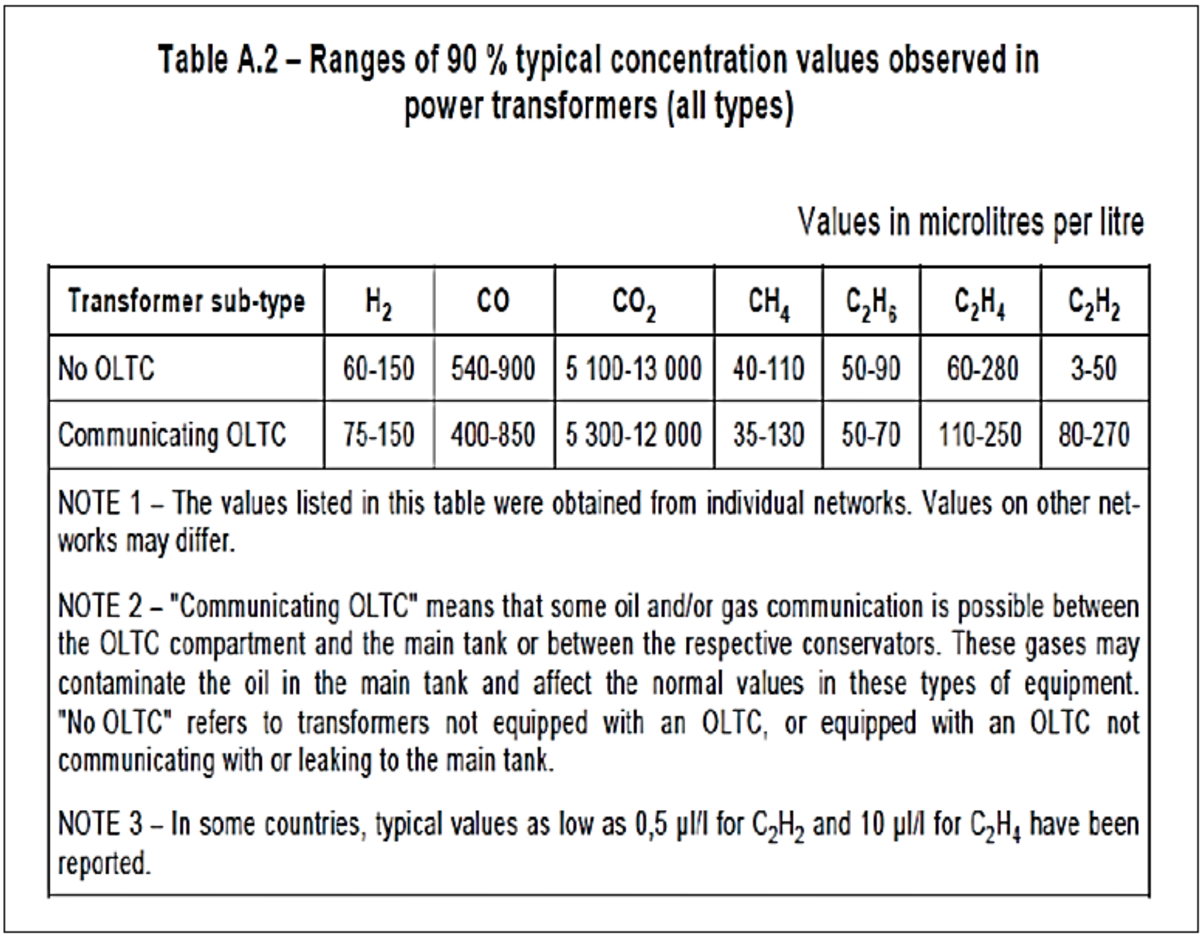


Table A.2 – Ranges of 90 % typical concentration values observed in power transformers (all types)

Values in microlitres per litre

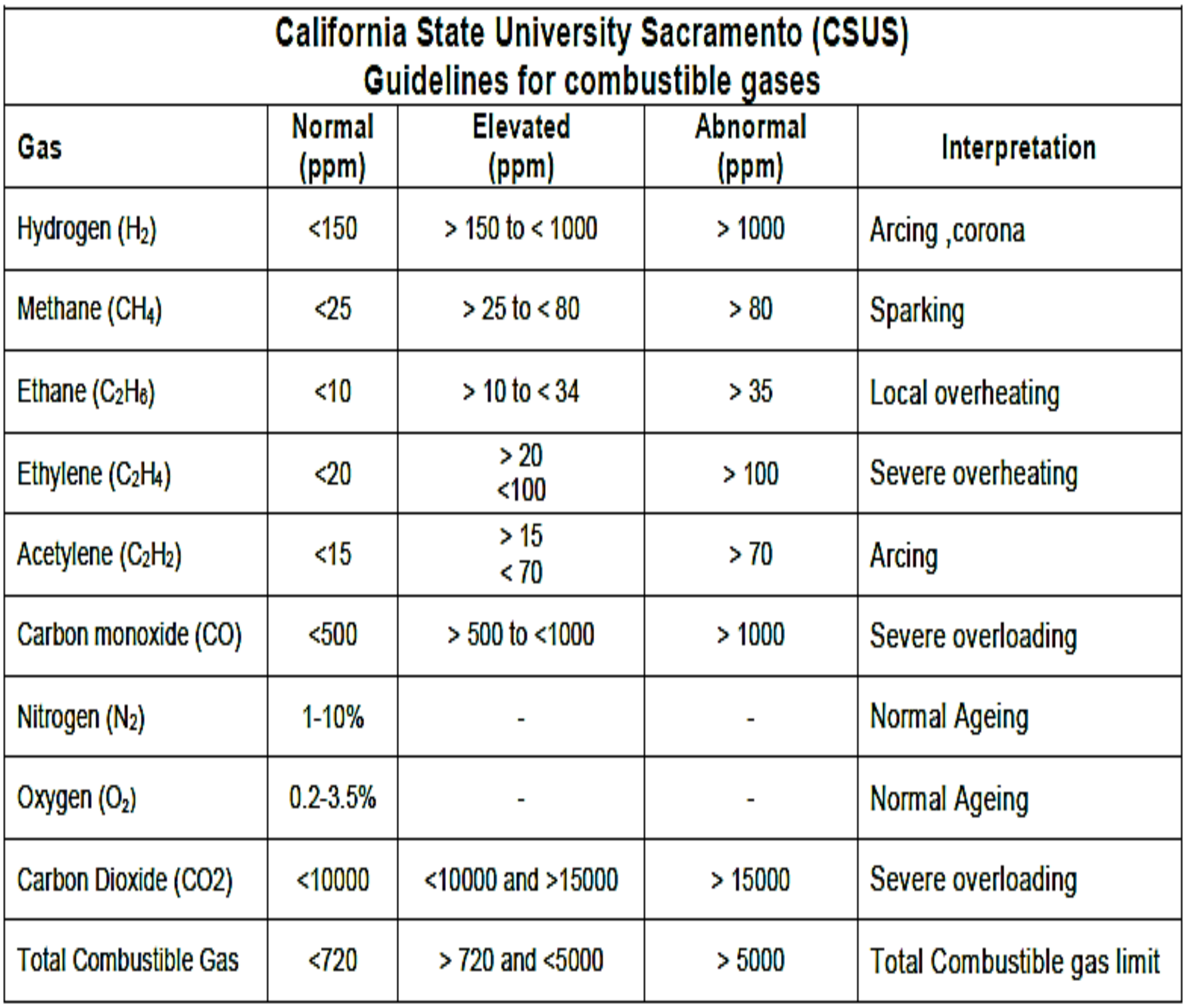
Transformer sub-type	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
No OLTC	60-150	540-900	5 100-13 000	40-110	50-90	60-280	3-50
Communicating OLTC	75-150	400-850	5 300-12 000	35-130	50-70	110-250	80-270

NOTE 1 – The values listed in this table were obtained from individual networks. Values on other networks may differ.

NOTE 2 – "Communicating OLTC" means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. These gases may contaminate the oil in the main tank and affect the normal values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with an OLTC not communicating with or leaking to the main tank.

NOTE 3 – In some countries, typical values as low as 0,5 µl/l for C_2H_2 and 10 µl/l for C_2H_4 have been reported.

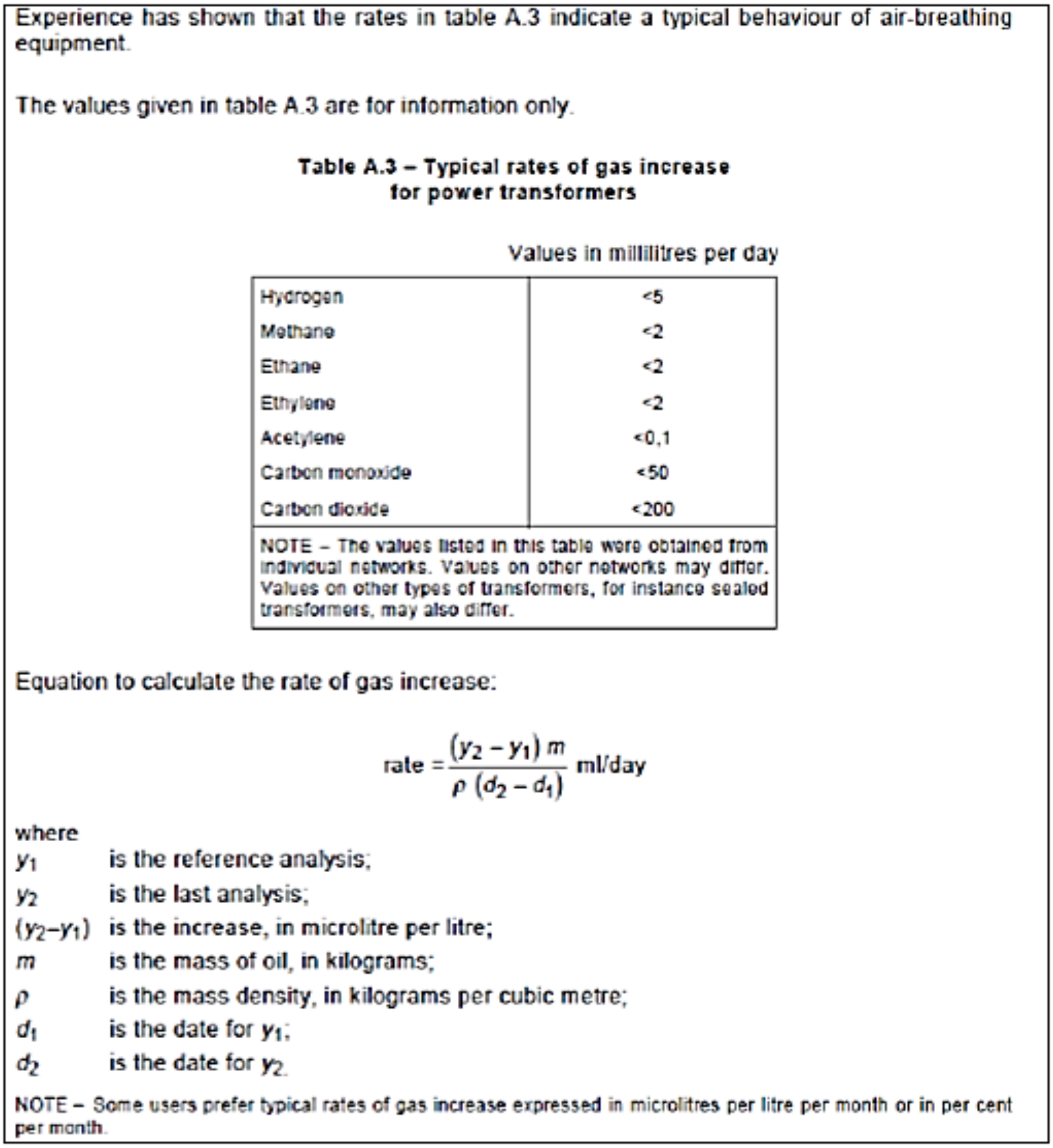
Annexure B: Extract from CSUS Guidelines on the evaluation of Dissolved Gas Levels in Power Transformers



California State University Sacramento (CSUS)
Guidelines for combustible gases

Gas	Normal (ppm)	Elevated (ppm)	Abnormal (ppm)	Interpretation
Hydrogen (H_2)	<150	> 150 to < 1000	> 1000	Arcing ,corona
Methane (CH_4)	<25	> 25 to < 80	> 80	Sparking
Ethane (C_2H_6)	<10	> 10 to < 34	> 35	Local overheating
Ethylene (C_2H_4)	<20	> 20 <100	> 100	Severe overheating
Acetylene (C_2H_2)	<15	> 15 < 70	> 70	Arcing
Carbon monoxide (CO)	<500	> 500 to <1000	> 1000	Severe overloading
Nitrogen (N_2)	1-10%	-	-	Normal Ageing
Oxygen (O_2)	0.2-3.5%	-	-	Normal Ageing
Carbon Dioxide (CO2)	<10000	<10000 and >15000	> 15000	Severe overloading
Total Combustible Gas	<720	> 720 and <5000	> 5000	Total Combustible gas limit

Annexure C: Extract from IEC 60599:2007 for Typical Production Rates for Power Transformers



Experience has shown that the rates in table A.3 indicate a typical behaviour of air-breathing equipment.

The values given in table A.3 are for information only.

Table A.3 – Typical rates of gas increase for power transformers

Values in millilitres per day

Hydrogen	<5
Methane	<2
Ethane	<2
Ethylene	<2
Acetylene	<0,1
Carbon monoxide	<50
Carbon dioxide	<200

NOTE – The values listed in this table were obtained from individual networks. Values on other networks may differ. Values on other types of transformers, for instance sealed transformers, may also differ.

Equation to calculate the rate of gas increase:

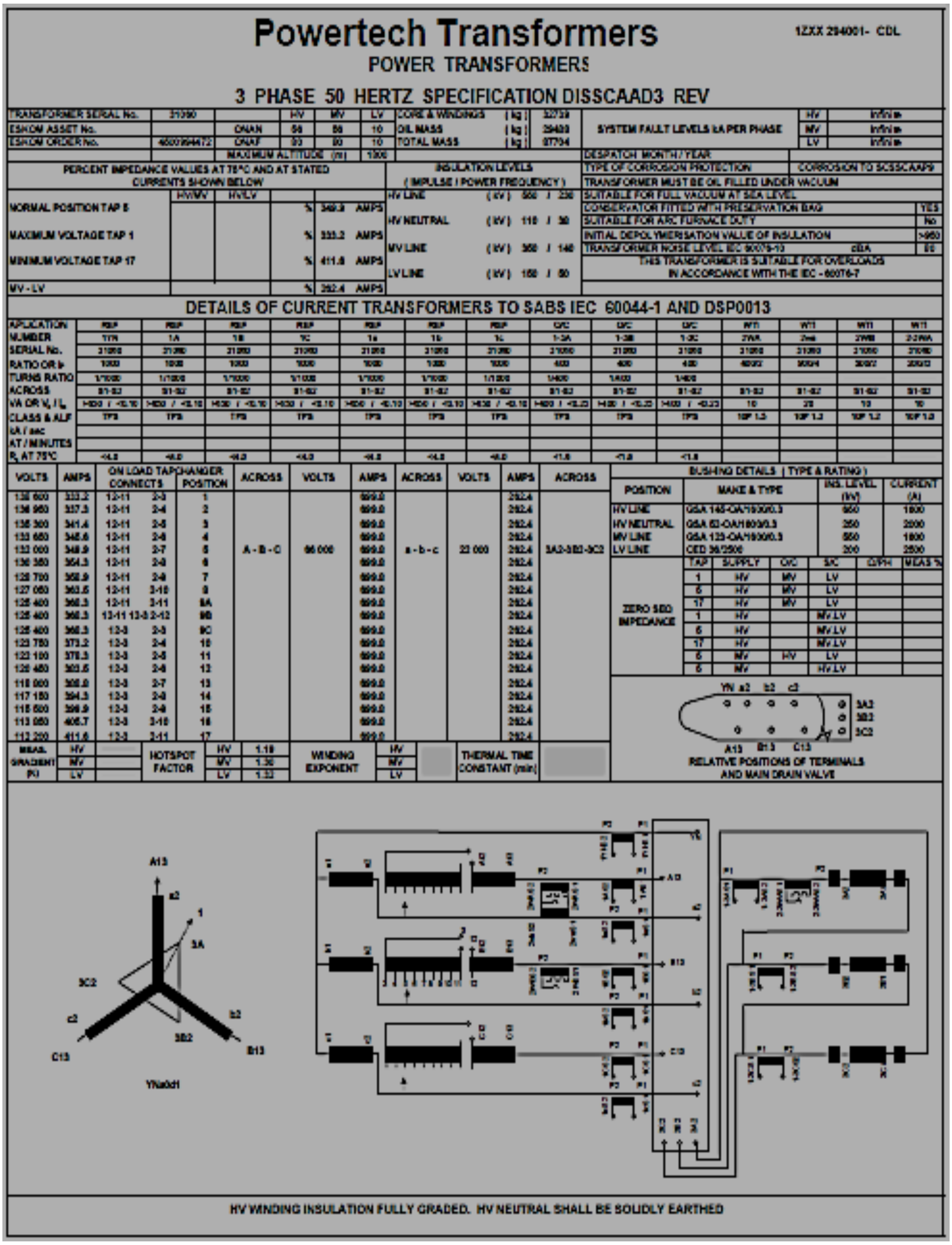
$$\text{rate} = \frac{(y_2 - y_1)\, m}{\rho\, (d_2 - d_1)} \text{ ml/day}$$

where

y_1	is the reference analysis;
y_2	is the last analysis;
$(y_2 - y_1)$	is the increase, in microlitre per litre;
m	is the mass of oil, in kilograms;
ρ	is the mass density, in kilograms per cubic metre;
d_1	is the date for y_1;
d_2	is the date for y_2.

NOTE – Some users prefer typical rates of gas increase expressed in microlitres per litre per month or in per cent per month.

Annexure D: Transformer Number 1 and Number 3 Nameplate at KDS



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POWER TRANSFORMERS

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DETAILS OF CURRENT TRANSFORMERS TO SABS IEC 60044-1 AND DSP0013

HV WINDING INSULATION FULLY GRADED. HV NEUTRAL SHALL BE SOLIDLY EARTHED

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