Power Transformer Health Assessment Derived From Low Energy and Dissolved Parameters

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A Thesis submitted to the Faculty of Engineering and the Built Environment in fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering

DECLARATION

I declare that this thesis is my own original work. Where collaborations with other researchers are involved, or materials generated by other researchers are included, the parties and/or materials are acknowledged or are explicitly referenced as appropriate.

This work is being submitted for the degree of Doctor of Philosophy in Engineering of the University of Cape Town, South Africa. The work contained herein has not been submitted to any other university or institution for any other degree or examination.

Signed by candidate

Signature Removed

________________________ October 2012

Nadarajan Moodley **Date**

Dedicated in loving memory of my Dad

Balakrishnan Mudaly

Thank you for instilling in me the value of education and continuous improvement

An Abstract of

Power Transformer Health Assessment
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Power transformers remain one of the key components of any power network and although passive in nature internally it hosts a dynamic environment of magnetic forces, chemical reactions and electrical activity which has to maintain the finest equilibrium to ensure long term sustainability.

After experiencing several power transformer failures within Eskom, a South African Power Utility, it was evident that the conventional condition assessment standards were inadequate as a forewarning tool. This dissertation studied the mechanisms of transformer health in terms of energy and dissolved parameters and establishes a novel method to identify a trigger for a change in transformer condition from normal to defective state.

The study took the form of both analytic research to create a low energy degradation model and then empirical testing of the model on field data in the form of dissolved gas analysis as recorded from 201 GSU transformers that have either failed or are presently in service.

The proposed model, Low Energy Degradation Triangle, is composed from the three dissolved gases hydrogen, methane and carbon monoxide. These three dissolved gases generally start to be formed from low energy degradation processes within the power transformer. The three gases are plotted as a triangular plot on a XY plane allowing for creation of specific regions and trends as the transformer insulation degrades under different operating conditions. The nature of the model is that it is sensitive to both degradation of the cellulose and oil insulation and the amount of energy that may be present.

The Low Energy Degradation Triangle provides an early detection of a change in transformer health from normal to defective state. This model is potentially effective when applied to on-line dissolved gas samples were trending of dissolved gases play a key role in detecting incipient changes in the level of insulation degradation. The advantage of this method is that it allows for the identification of a change in transformer health status caused by degradation mechanisms developing from low energy sources. The Low Energy Degradation Triangle has been successfully applied to the GSU transformer fleet within Eskom where significant defective transformer health statuses have been identified and highlighted as a warning for intense monitoring.

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To my darling wife and loving son, I really tried to create a balance, but thank you for your patience and support in allowing me your invaluable time to complete one of my life's goals. Without you this journey would have been a lonely one.

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LIST OF SYMBOLS

ANN	Artificial Neural Network
CH_4	Methane
C_2H_4	Ethylene
C_2H_6	Ethane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
°C	Degrees Celsius
DGA	Dissolved Gas Analysis
DP	Degree of Polymerisation
GIC	Geomagnetic Induced Currents
GSU	Generator Step Up
H_2	Hydrogen
H_2O	Water
HV	High Voltage
HVDC	High Voltage Direct Current
Hz	Hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IFT	Interfacial Tension
kV	Kilovolt
LEDT	Low Energy Degradation Triangle
LV	Low voltage
MVA	Mega Volt Amps
O_2	Oxygen
OCGT	Open Cycle Gas Turbine
PD	Partial Discharge
ppm	parts per million
YOM	Year of Manufacture

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CHAPTER 1

INTRODUCTION

It was 00H25 on 29 November 2001. I just received a distressing call from the plant operator on one of the hydro power stations in South Africa who conveyed to me that Unit 4 tripped on GSU transformer Buchholz protection. They checked the transformer and found a large puddle of oil near the pressure relief belch pipe. I was then requested for the actions to be taken.

As a transformer system engineer, this was my first experience of a GSU transformer failure. Eskom (a South African Power Utility) has a large fleet of GSU transformers and there was starting to be an increase in the number of failures. One of the challenges of power utilities and major industries is the effective asset management of equipment and having a clear indication of when critical equipment will fail so that mitigation strategies can be put in place to reduce the impact of such failures. Usually when such interventions are implemented, these may be too early where full use of assets is not achieved. The health of assets has remained an approximated parameter although it plays a quintessential role in the asset management process.

This event took me by surprise. There was no indication of an inherent problem. Numerous techniques have been developed over the years for the identification of incipient faults in power transformers. These were religiously applied as part of the transformer condition monitoring program. Something was missing. Why did we not have any prior indication of this failure?

This was the start of my journey to create a health assessment model to detect early change in the transformer state from that of normal to defective.

1.1. DEFINITION OF THE RESEARCH PROBLEM

Over the last 10 years, industries and power utilities within Southern Africa have been experiencing a significant number of transformer failures [Oommen1]. This resulted in high-unplanned capital expenditure with consequential production losses running into hundreds of millions of Rand and adversely affecting the market and the economic growth of the country. Failure statistics within Eskom for the period 2007-2008 suggested that a significant number of GSU transformer failures were attributed to thermal mode failures of the winding, winding connections and cooling system [Jagers1]. Some correlation has also been made to thermal stress caused by geomagnetic induced current during solar storms [Gaunt1]. These failures have suggested that conventional incipient fault diagnosis methodology might not be effective in predicting early low energy source failures and does not prepare one for such a failure until it was in the advanced stages of faulting where expensive recovery interventions have to be suddenly enforced.

The life of the power transformer is directly related to the life of the insulating material [McNutt1]. The copper strands of the windings are insulated by Kraft paper insulation and the core is manufactured from sheets of steel that are individually insulated by a thin film of insulating coating, surrounded in oil. All the insulating materials are affected by changes in energy levels that are generally converted into heat in areas of localised hot spots.

Transformers by natural ageing produce particles and dissolved gases where dissolved gas analysis in the oil has long been identified as one of the key non-intrusive methods of identifying internal faults within an oil filled power transformers [Haupert1]. However, failures of transformers are still unexpected and are not caught early in its fault life cycle. From historical experience, conventions have been developed on the levels of gases for normal operation and fault conditions but interpretation is still dependent on expert knowledge of the field and may not be readily available to identify incipient failures until the condition becomes visibly severe. Vast experience is required to effectively apply present fault diagnosis methods as many aspects such as running conditions, design, manufacturing quality and maintenance can affect the diagnosis of the different techniques.

Most transformer failures are identified with the operation of a protection device such as electrical protection or mechanical such as a Buchholz relay. Without these devices, the transformer failure is usually catastrophic. Dissolved oil samples are generally taken routinely but may be at intervals of a few months. During this period, there can be a vast progression of incipient faults. Thus, it is very important with the advancement of technology that reliable on-line continuous monitoring be provided with relevant triggers to identify the onset of defective conditions within the power transformer.

Some incipient fault identification methods such as Rogers, Key Gas, and IEEE may identify some incipient faults; however, these methods are not consistent and usually misdiagnose defective conditions in other transformers. The full spectrum of fault conditions cannot always be adequately covered by any one method.

The other aspect of normal ageing as a result of operating temperatures from losses and chemical reactions was the production of byproducts from oil consisting of hydrogen, methane, ethane and some ethylene [McNutt1]. The paper degradation produces carbon monoxide and carbon dioxide [Kachler1]. These gases could sometimes be produced at elevated levels and be mistaken as a fault condition. These must be effectively distinguished from that of true fault conditions.

The majority of the work in this field focused on incipient fault diagnosis with general transformer health inferred from such diagnosis. Yet healthy transformers (no defects identified) have suddenly failed, resulting in huge financial and asset loss. The conventional fault diagnosis methodology is not as effective in providing a prospective approach to transformer condition assessment. When faults are picked up it is already too late and has progressed to an advanced state so that mitigation strategies only allow for containment and management of damage to the external environment.

1.2. AIM OF THE RESEARCH

GSU transformers transfer energy from generating units to the transmission network by stepping up the generator voltage. This process is efficient but changes of energy levels within the transformer due to defective conditions can affect the integrity of the transformer. Different fault conditions produce different levels of energy and heat transfer.

The aim of this study is to use analytical methods to identify the impact of low energy changes within a transformer, thereby creating a model for identifying normal and negative health conditions in power transformers. The model will then be used to identify health diagnosis parameters to clearly define incipient fault prediction with specific focus on the influence of thermal and electrical faults within the power transformer.

This study tests the hypothesis that *low energy changes within a power transformer affect the composition of dissolved parameters in such a way that allows the effective identification of insulation degradation and incipient faults.*

The focus is on the interpretation methodology and failure mechanisms arising from energy sources producing low levels of dissolved gases and the ability to assess transformer life with respect to successfully absorbing sudden external stresses. The study proposes an approach for assessing transformer health based on dissolved gas parameters and associated interactions for low energy sources within the power transformer.

1.3. RESEARCH QUESTIONS

The following research questions need to be answered to test the validity of the hypothesis:

- What are the shortcomings of the existing incipient faults identification methods?
- What mechanisms are required for decomposition of oil and paper?
- How do these mechanisms affect transformer health?
- How does the energy inside the transformer change for normal and fault conditions?
- What are low energy failure mechanisms and how can these be identified?
- What factors affect dissolved gas trends?
- How do dissolved gases react under different energy conditions?
- How does Geomagnetic Induced Currents affect the energy changes within the transformer? Can the effects of GIC be identified?

1.4. RESEARCH METHODOLOGY

Figure 1-1 provides a diagrammatic overview of the structure of this study. Literature research forms the basis of the first part of the study, which starts with the general research on transformer health and failure statistics of transformers around the world and within South Africa. From this research, a baseline is formed on the failure mechanisms, types of faults and ageing trends that are used for the health assessment model.

A key aspect of this research entailed the identification of defective energy sources and the related impact on the transformer health. The main outcome of this investigation was to clearly define the components of the transformer that limit the transformer in terms of operating condition to fulfil or extend its intended design life. Theory of the failure mechanisms contributes by further defining the degradation parameters that will allow for the effective condition monitoring of the key components of the transformer. All of these concepts are then utilised to create a theoretical model that will allow for the detection of normal and defective states of a power transformer.

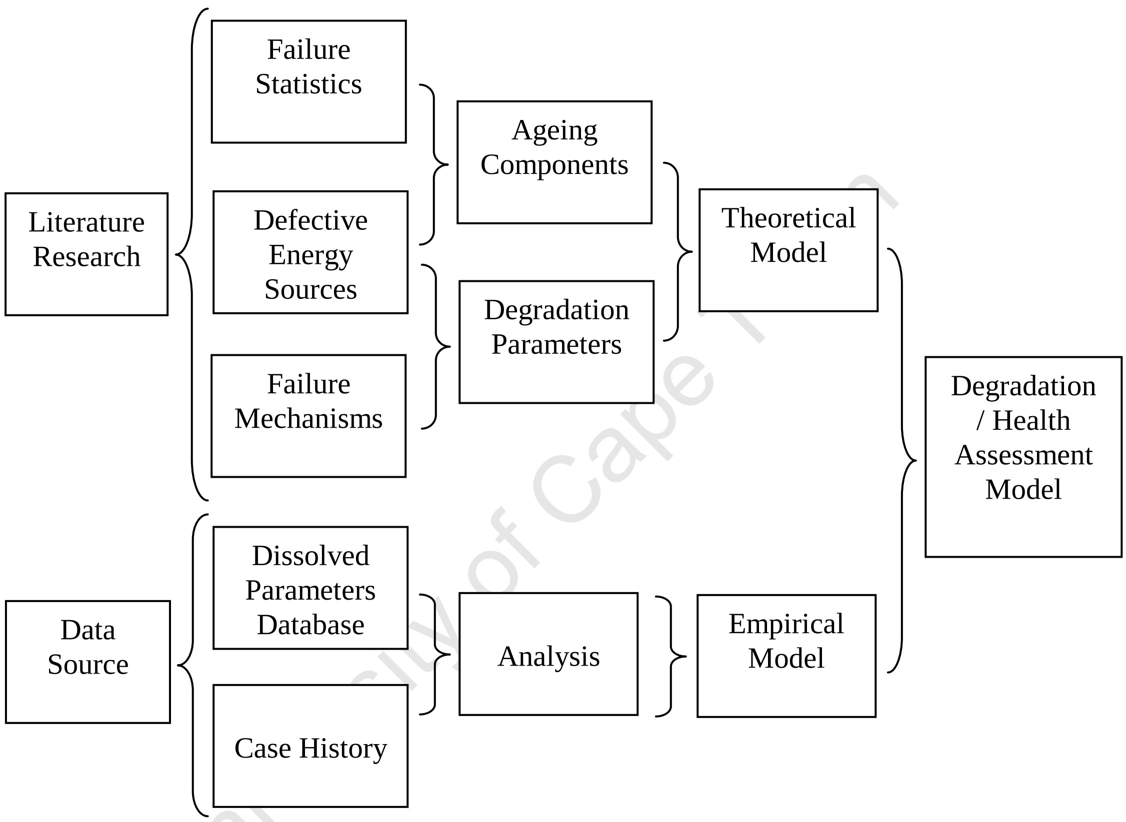


Figure 1-1: Study Methodology

The second part of this study consisted of an intensive health assessment investigation into the physical assets within Eskom. The intention of this part of the study was to utilise the invaluable experiences of transformer health challenges within the power utility. In recent years, Eskom has experienced a significant number of failures. These failures have been linked to various reasons; design, aging, insufficient cooling of windings and symptoms of geomagnetic induced currents [Gaunt1]. The data for this study covers the fleet of GSU transformers within Eskom and takes the form of dissolved parameters obtained from on-site transformer mineral oil samples. These samples consisted of the majority of tin samples and of on-line samples taken on a few GSU transformers that were fitted with on-line gas analysers. The database consisted of 201 GSU transformers (ranging from 65 MVA to 760 MVA) and 12950 oil samples that range in date from 15-01-1987 to 06-05-2012.

This study identifies the critical components of the transformer and its impact on the transformer life where focus was limited to the internal of the transformer and excluded auxiliary equipment such as the bushing, tap changer, cooling and other attachments.

The study focused on identifying degradation profiles for thermal, electrical and low energy internal failures within power transformers that are then used for individual analysis to establish a logical flow of developing faults and progression of what is happening inside the transformer.

Part of this study was to identify degradation patterns for each type of insulation material and to formulate relevant indicators to provide information for the maintenance engineer on the risk of transformer failures and asset management strategies. An assumption made was that the paper type is of normal Kraft paper. The characteristics of the cellulose paper/board under load conditions are researched to identify parameters for normal aging and for defective aging under overload conditions. Saha identified that the insulation system of a power transformer was composed predominantly of hydrocarbon, oil and paper that degraded at higher operating temperatures in the presence of oxygen and moisture [Saha1]. A key point of degradation is the paper insulation making up the windings of the transformer, which includes the high voltage, low voltage and regulating windings together with the leads. The second assumption made in this study was that the insulating oil used was that of transformer mineral oil. The specific characteristics of oil will be studied and how it reacts under different loading conditions. The questions, how does oil age, what happens to it under long term and fault conditions and how does it contribute to the aging of the more permanent components, are investigated.

The final insulation degradation model was intended to take into account the effects of the energy dissipated within the transformer under different fault conditions and how these conditions can be identified by means of dissolved gas parameters.

1.5. STRUCTURE OF THE PHD THESIS

The following section provides a brief outline of the chapters.

Chapter 2 reviews the existing knowledge on the subject of transformer component health, fault diagnosis and failure statistics, characteristics of dissolved gas parameters and insulation degradation processes. A brief review is made on the current generally accepted fault identification methods.

Chapter 3 starts by investigating the insulation degradation mechanisms and how these affect the health status of the transformer. The formulation of the Severity-Lifespan approach is made setting the scene for the development of a diagnostic methodology for low energy incipient faults. This chapter also defines the theory in terms of defective energy conditions within a power transformer and then leads the investigation into identifying the main low energy dissolved parameters that can be used as a condition-monitoring element.

Chapter 4 formulates the development of the Low Energy Degradation Triangle. Details are provided on how the triangle is intended for use, the specific information that can be obtained from the different regions and the possible trends as linked to insulation degradation and fault progression.

Chapter 5 further investigates the capabilities of the Low Energy Degradation Triangle in providing an indication of the level of degradation and related energy levels within the transformer. This section provides more refinement to the Low Energy Degradation Triangle.

Chapter 6 provides a detailed analysis of specific case studies of transformers that have failed or was removed from service within the Eskom GSU transformer fleet. There were 12 case studies used in the application of the Low Energy Degradation Triangle.

Chapter 7 covers the discussion of results for the more general analysis of the dissolved gas data and its impact on the transformer health using the Low Energy Degradation Triangle.

Chapter 8 summarizes the conclusions from this study.

1.6. PUBLICATIONS

Some of the findings of this thesis have been presented at national and international conferences [Moodley1, Moodley2].

CHAPTER 2

REVIEW OF EXISTING KNOWLEDGE

2.1. INTRODUCTION

Chapter one provided a background of this study, the challenges facing a transformer asset manager to identify the health of a power transformer and when it must be taken out of service for maintenance, repair or replacement. The notion that transformer faults generally initiates from low energy degradation mechanisms before developing into a mature fault was introduced as a starting point in this study [Emsley1].

Chapter two starts off with a review of past power transformer failures and statistics to identify the general aspects and trends for transformer health. Then a detailed exploration was made of the theory behind the health of a power transformer, covering the degradation mechanisms of the different aging components with corresponding by-products. Further investigation was made in the current methods available for assessing transformer health and the identification of incipient faults.

2.2. TRANSFORMER FAILURES AND STATISTICS

Power transformers form an important component of the modern interconnected power system and are usually reliable with a design life of 20-35 years although some transformers could have a life of up to 60 years depending on appropriate maintenance [Wang1]. Industry engineers believe that transformers have an expected life of 30 to 40 years, but in Hartford Steam Boiler study, the data showed the average age at failure was 14.9 years [Bartley1]. The mean age at failure for utility transformers as recorded for Eskom was 17.7 years [Jagers1].

A detailed failure study conducted within Eskom on GSU transformers over the period 2007-8 revealed the following conclusions [Jagers2]:

- The overall annual failure rate was 4 % per annum
- A significant number of failures developed in the winding connections and as thermal mode failures due to inherent material defects
- 29% of transformers were between the age of 5-10 years, 14% between 10-15 years, 14% between 20-25 years and 43% between 30-35 years
- Failure locations within GSU transformers were as follows; cooling 17%, tap changer 17%, windings, 17%, winding connections 49%
- The failure modes were identified as; electrical 14%, mechanical 14%, physical chemistry 14% and thermal 58%

2.3. TRANSFORMER LIFE

The key aspect of transformer winding construction is the insulation of each conductor with paper that is impregnated with insulating oil, providing at least a minimum life of 25 years at an operating temperature of 65-95 °C [Emsley2]. The end of life of a transformer occurs when the mechanical strength of the solid insulation in the windings was lost and failures are then triggered by severe conditions like lightning strikes, switching transients and short-circuits [Emsley2, Kachler1, Wang1]. Wang et al. highlighted that transformer failures can be categorized as electrical, mechanical or thermal where the cause of failure being either internal or external [Wang1].

Generator and furnace transformers exhibit accelerated aging in comparison to grid transformers due to the high loading factors [Kachler1]. Generator transformers are often loaded to full rating, which can increase the aging rate due to higher winding temperatures causing faster rates of insulation paper de-polymerisation [Checksfield1].

Insulating materials age thermally and from chemical reactions occurring within the materials caused by pyrolysis, oxidation and hydrolysis, which are accelerated by increased levels of temperature, oxygen and moisture content [McNutt1, Wang1].

An unusual gassing state defined as ‘stray gassing’ was identified as a phenomenon where some types of insulating oils produced hydrogen and hydrocarbons when heated at low temperatures of around 100°C to 120°C. However, the gas formation subsides to plateau off and this gas level can be removed by filtering the oil [Hohlein1].

External faults easily increase the short circuit forces to dangerous proportions such that any hidden defects and aged insulation causes inter-turn shorting [Wang2]. Internal faults frequently occur on one phase of the HV winding and can be formed either by direct contact or by an electric arc [Jablonski1]. With system growth, transformer loading increases causing the operating stress to increase. This causes the conductor insulation to weaken in an aging transformer to the point where it can no longer sustain mechanical stresses of a fault. Dielectric failure of turn-to-turn insulation causes loosening of winding clamping pressure, which reduces the transformer's ability to withstand future short circuit forces [Bartley1].

2.4. AGING COMPONENTS AND BY-PRODUCTS

2.4.1. Main Structures

A power transformer is composed of a core, set of windings, oil, tank, bushings, tap changer and other auxiliary equipment. Each of these components is manufactured from either metals or compounds that are organic in nature. The different types of material react differently to the different fault conditions and the rate of energy release in the vicinity. This study examines the effects of the energy dissipated and the rate of breakdown of the different materials. These materials consist of kraft paper, oil, copper, steel and insulating boards.

The transformer tank is manufactured from steel and houses the oil and active part of the transformer. The tank has to be properly earthed and can sometimes be subjected to circulating currents causing localised hot spots.

The transformer core provides the medium for the flux path. It is usually manufactured from steel, which is arranged as thin laminations for reducing the effects of eddy currents. These laminated sheets are usually coated with a layer of special varnish or shellac [Gottlieb1].

The core arrangement is usually constructed in either the core or the shell type arrangement. The core type arrangement is such that the magnetic core is surrounded by the low voltage and high voltage windings [Heathcote1]. In the shell type arrangement the windings are surrounded by the core. GSU Transformers are usually of the core type arrangement. The core arrangement also can have a variation on the number of limbs. In a five limb core type transformer the three phase windings are located in the inner three core legs respectively and the outer legs on either side allow for flux transfer.

GSU transformers are constructed as two winding transformers. The low voltage and high voltage winding per phase are located in close proximity to ensure the maximum mutual coupling between windings [Winders1]. The windings are composed of thin copper strands, which are wrapped with paper insulation. Details of the paper insulation are provided in section 2.4.2.1.

2.4.2. Organic Compounds

The power transformer basic components, which are organic in nature, are the insulating oil and cellulose based insulation (paper, insulation boards and blocks) [Heathcote1]. These components form the basis for the transformer health or life, as these are usually the fastest degrading materials making up the transformer [Emsley2].

2.4.2.1. Solid Insulation

The solid insulation is composed of Kraft paper, pressboard, transformer board and cellulose made up of electrical grade paper insulation manufactured from unbleached sulphate cellulose [IEEE 60641-3-1].

Kraft paper has a cellulose base that is composed of linear, polymeric chains of cyclic β-D-glucopyranosyl units [Lundgaard1]. These chains consist of linear condensation polymer, which is composed of a hydrocarbon glucose molecule that is formed by D-anhydroglucopyranose units joined by ß 1.4 – glucosidic bonds. Paper insulation has a general molecular formula of $[C_{12}H_{14}O_4(OH)_6]_n$ with n in the range of 300 to 750 [DiGiorgio1]. The cellulose breaks down causing the lengths of the chains to become smaller with the process generating CO, CO_2 and H_2O [Wilkinson1]. Other products produced during this breakdown process like –OH and –OH2OH groups further promote the cellulose to become both hygroscopic and vulnerable to oxidative degradation [Oommen3, Unsworth1]. Water is found in the paper insulation as a vapour, absorbed to surfaces, as free water in the capillaries and as imbibed free water [Du1]. The presence of moisture plays a critical role in the life of the transformer insulation [Lundgaard1].

Acid-hydrolysis, pyrolysis and oxidation are processes, which causes the depolymerization of paper [McNutt1, Lundgaard1, Unsworth1]. Oxidation is a process that is considered a form of combustion where the products of the reaction are water and carbon dioxide. Pyrolysis and thermal heating of the paper insulation produces significant amounts of CO and CO_2 [Emsley2, Griffin1].

Studies have found that Insuldur upgraded paper does not produce as much 2FAL as Kraft paper concluding that 2FAL cannot be used as an indicator of ageing for all paper types [Lundgaard1, Prevost1]. Although both water and oxygen play an important role in the paper degradation process, water is the most significant contributor because the catalytic efficiency of dry acids is low [Lundgaard1].

2.4.2.2. Mineral Insulating Oil

Transformer mineral insulating oil is composed from naphthenic crude oils which is a mixture of hydrocarbon compounds of alkanes, naphthenes and aromatic hydrocarbons. Mineral oil has a general molecular formula of C_nH_{2n+2} with n in the range of 20 to 40 [DiGiorgio1].

The transformer mineral oil has numerous particles and compounds dissolved within it. These compounds are as a result of byproducts in the degradation process or being introduced from the external environment. The most common are dissolved gases, acids, water, corrosive sulphur, silicon and furans. Insulating oil by nature has a low affinity for water but the solubility increases significantly with an increase in temperature. It is further highlighted that water can exist in transformers in a dissolved state in oil, tightly bound to the oil molecules or as free water [Du1]. Aging of oil insulation is markedly different for open (free breathing) and closed systems [Kachler1]. Aging of the oil insulation is accelerated by the high ingress of oxygen, which after reaching equilibrium of approximately 20000 ppm produces a source of additional energy for the ageing of the oil [Ferguson1]. Transformer oil degradation is primarily caused by decomposition, contamination and oxidation [Phadungthin1]. Mineral oil may break down under elevated temperatures due to abnormal loading or fault conditions such localised hotspots and electrical faults. Moisture, dielectric, acidity and oxygen have a major effect on the ageing and break down of the oil [Cigre WG12.18].

For thermal conditions such as pyrolysis in oil significant levels of ethylene are produced supported by hydrogen and methane [Wang1]. Arcing in oil causes significant levels of both hydrogen and acetylene to be produced [Kelly1].

2.4.3. Dissolved Gases

Dielectric oil and solid cellulose dielectric materials when degrading under thermal and electrical stresses produce gases of varying compositions and in concentrations relative to the severity of the stresses applied to these materials [Griffin1]. These gases dissolve in the oil where the nature and concentrations of the dissolved gases sampled provides a good representation of the type and severity of the fault in the transformer [Rogers1]. The changes in the gas production rates form key components in the determination of the type of fault(s) involved where some specific gases form profiles for certain types of faults [Gibeault1].

Dissolved gas data are obtained from oil sample testing [IEC 60567]. The most common gases analysed from oil tests are hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and nitrogen (N_2) [Wang1].

The degradation of oil insulation material produces a fair amount of hydrocarbon compounds, which are composed of hydrogen and carbon atoms that are broken up into two distinct classes, namely aliphatic and aromatic hydrocarbons [Arora1]. Aliphatic hydrocarbons are further broken down into three groups, which are alkanes, alkynes and alkenes. Alkanes are composed of single bonds, alkenes consist of double carbon bonds and alkynes consist of triple carbon bonds [Arora1]. This means that more energy is required for the breakdown of double and triple bonds implying that less energy is required for gases such as methane and ethane and higher energy for ethylene and acetylene.

The principle degradation product of low energy electrical discharges found in mineral oil-filled transformers are molecular hydrogen [Rouse1].

The decomposition of methane (CH_4) into its elements starts at about 578°C hence competes with its degradation to acetylene [Leroux1].

The formation of ethylene and acetylene has been noted to be specific to high-energy electrical discharges [Arakelian1]. At about 1327°C and higher, acetylene is more stable than other hydrocarbons but decomposes into its elements thus indicating that the conversion or splitting time must be incredibly short (milliseconds) [Leroux1]. The amount of energy needed is very large and in the region of the favourable free energy.

All hydrocarbons release carbon dioxide and H_2O as products of combustion [Arora1]. Studies have shown that the thermal decomposition of cellulose insulation produces carbon oxides (CO and CO_2), some hydrogen and methane due to the oil impregnation [Kachler1, Wang1]. The oxygen levels in the transformer arise primarily from the atmosphere. Oxygen causes oxidation of the oil, which sustains the insulation degradation process [Liland1].

Solubility

Different gases/parameters have different solubility levels in mineral oil [DiGiorgio1]. It is important to correctly identify the levels of gases produced in the associated defective conditions before any dissolved gas analysis is attempted.

The following table 2.1 provides solubility levels of the gases in transformer mineral oil with a static equilibrium at 760mm Hg and 25 °C [DiGiorgio1]:

Table 2.1: Typical solubility levels of gases in mineral oil [DiGiorgio1]

Gases	Solubility
H_2	7% by volume
N_2	8.6%
CO	9%
O_2	16%
CH_4	30%
CO_2	120%
C_2H_6	280%
C_2H_4	280%
C_2H_2	400%

Figure 2-1 provides some indication of the relative solubility of the combustible gases as a function of temperature [DiGiorgio1]. Gases such as hydrogen, nitrogen, carbon monoxide and oxygen have an increasing solubility rate with increasing temperature. The hydrocarbon gases methane, acetylene, ethylene and ethane together with carbon dioxide have a decreasing solubility rate with increasing temperature. It is noted that both hydrogen and carbon monoxide are not very soluble at low temperatures but the solubility rate does improve drastically for hydrogen at operating temperatures around 70-80°C. The solubility rate of methane is moderate, decreasing with increasing temperatures. These aspects play an important role and must be taken into consideration when assessing the gas production rates as assessed from oil samples.

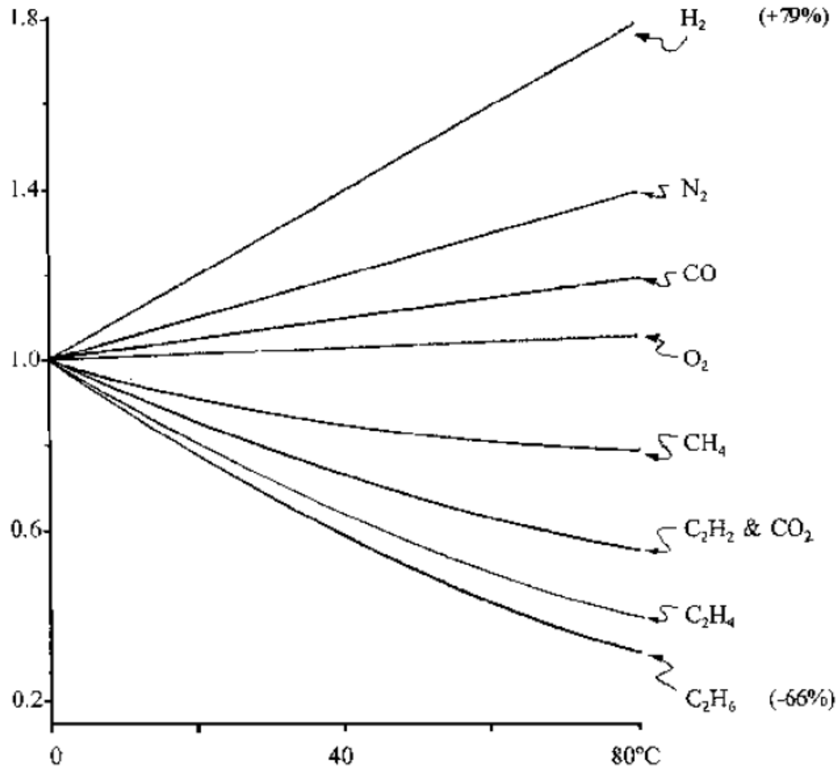


Figure 2-1: Relative Solubility as a function of Temperature [DiGiorgio1]

2.5. DISSOLVED GAS ANALYSIS METHODS

Power transformers play a key role in any power network and must be maintained and effectively monitored with continuous condition assessment to ensure reliability of the network. Numerous techniques have been developed over the years for the detection of transformer faults. Some of the conventional parameters used are dissolved gases, furfuraldehyde, degree of polymerisation of paper insulation and frequency response analysis. Dissolved gas analysis has been extensively utilised for incipient fault detection by some of the following methods; key gas analysis [IEC60567], the Dornenburg [Dornenburg1], Duval [Duval1], Rogers [Rogers1] gas ratio method and those highlighted in the ANSI/IEEE standard [IEEE C57.104]. Other advanced analytical techniques explored are artificial neural networks, fuzzy logic, data mining and cluster analysis with the aim of identifying fault conditions within the transformer.

This section provides a short review of the capabilities of the generally accepted fault diagnosis methods.

2.5.1. Key Gases Method

The Key Gas method focuses on the levels of the individual gases generated as a result of the breakdown of insulating material after a fault [IEEE C57.104, IEC 60567]. Prevalence of a certain gas infers a corresponding fault diagnosis. Conventional key gases are composed of hydrogen (H_2), hydrocarbons (CH_4, C_2H_2, C_2H_4, and C_2H_6) and carbon oxides (CO and CO_2).

This method associates high levels of the key gas hydrogen with that of partial discharges or corona in oil. Methane and ethane are associated with low temperature overheating of oil, ethylene with high temperature overheating of oil, carbon monoxide and carbon dioxide with overheating of cellulose and acetylene with arcing.

The challenge with this method is that most oil sample profiles do not usually fit into the key gas profiles and this method is not able to distinguish between more than one fault mechanism happening at the same time.

2.5.2. Dornenburg Ratio Method

The Dornenburg ratio method makes use of the ratios of the concentration of the key gases hydrogen, methane, ethane, ethylene and acetylene. The following ratios are used CH_4/H_2, C_2H_2/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4.

For this method to be a viable diagnostic tool a few criteria have to be met. This in itself is the negative aspect of this diagnosis method as there are more frequent than not "no diagnosis" obtained.

The criteria are such that for the transformer to be considered to have a problem at least one of the key gas concentrations must exceed twice a predetermined limit with at least one of the remaining three key gases exceeding its predetermined limit. There is also a further validity check that at least one of the key gases in each of the four ratios must exceed the predetermined limit for the ratios to be significant. Only then can the combination be compared to the codes. Once this criteria is met the combination of the ratios into a code is established, where each four parameter code has a unique diagnosis that is able to identify thermal faults, corona discharge and arcing [IEEE C57.104].

2.5.3. Rogers Ratio

The Rogers Ratio method is another ratio method very similar to the Dornenburg method with the ratios CH_4/H_2, C_2H_4/C_2H_6, C_2H_2/C_2H_4 and C_2H_6/CH_4. The combination of these ratios identifies a four-combination code with a lookup table of possible fault conditions. [Rogers1].

2.5.4. Duval

The Duval Triangle Method makes use of the three combustible gases CH_4, C_2H_4 and C_2H_2 that are transformed for representation in a triangular plot. The triangle is able to differentiate the fault types partial discharges, electrical faults (high and low energy arcing), and thermal faults (hot spots of various temperature ranges). Each point is derived from the percentage volume of the sum of the three gases. The triangle has a clockwise direction in terms of increasing percentage gas levels. Figure 2-2 presents the triangle with the definition of the six fault diagnosis regions [Duval1].

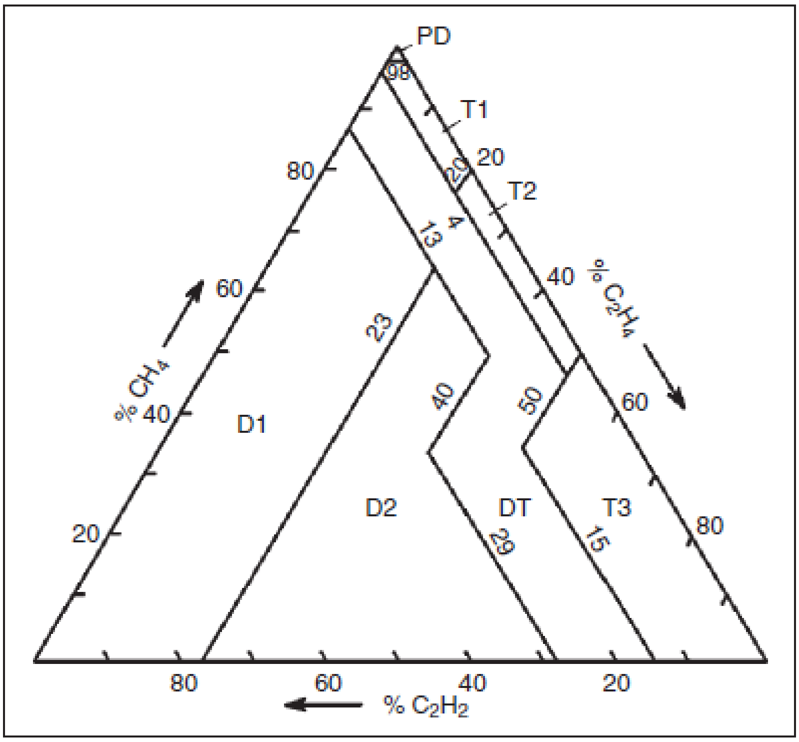


Figure 2-2: Duval's Triangle [Duval1]

The Duval triangle is very useful in providing diagnoses when a fault condition is already identified due to fact that two of the three gases used (ethylene and acetylene) are products of high energy conditions. The conditions identified are partial discharges (PD), discharges of low energy (D1), discharges of high energy (D2), thermal faults of temperature < 300°C (T1), thermal faults of temperature 300°C < T < 700°C (T2), thermal faults of temperature > 700°C (T3).

One of the key challenges of this method is that there is no region in the triangle to indicate a normal ageing state for the transformer. Thus this method is not as effective in identifying a change from normal to defective state.

An updated version, the Duval triangle 4 is composed of the three gases H_2, CH_4 and C_2H_6 which is more specific for low energy or temperature (PD, T1 and T2) [Duval5]. The Duval Triangle 5 is composed of the gases CH_4, C_2H_4 and C_2H_6 which is formed more specifically for the identification of faults of high temperature to ascertain more information about thermal faults in paper and oil [Duval5].

2.5.5. Contemporary Methods

Esp et al. have used typical analysis methods relating to oil, which includes dissolved gas analysis (DGA), colour, moisture level, acidity, breakdown voltage and furfuraldehyde content together with unsupervised neural networks to unearth further information [Esp1]. Ashkezari et al. through the multivariate analysis method was able to provide correlation among the relevant transformer oil tests consisting of moisture content, acidity, dielectric dissipation factor, resisitivity, breakdown voltage and 2-Furfural [Ashkezari1].

Chen and Lin displayed that diagnosing fault conditions from the combination of several simple fuzzy approaches are much better than traditional methods especially for transformers, which have gas-in-oil conditions around the crisp norms [Chen1]. Guardado et al. presented a comparative study of neural network efficiency for the detection of incipient faults in power transformers according to the Dornenburg, modified Rogers, Rogers, IEC and California State University of Sacramento (CSUS) criteria [Guardado1]. This study showed that the neural network rate of successful diagnosis is dependent on the criterion under consideration, with values in the range of 87-100%. Ding et al. Studied the relationship between transformer faults of power transformers and gases dissolved in insulating oil where preliminary simulation results showed a 95% correct diagnosis rate for the artificial neural network (ANN) based method with a modest amount of training data [Ding1]. Zhang et al. presented a two-step ANN method to detect faults with or without cellulose involved where good diagnostic accuracy is obtained with the proposed approach [Zhang1]. Chengbiao et al. used principal component analysis to extract information on the main characteristics of transformer fault diagnosis [Chengbiao1]. However, the results of this study indicated a loss of useful information.

Several authors have used DP as a diagnostic tool to determine the condition of transformers [Moser1, Shroff1, Allan1, Oommen2]. The following studies propose that for a DP of 150, the strength is reduced to 20% of its initial DP value and below this strength will be diminished to almost insignificant tensile strength [Fallou1, Shroff1, Hernadi1, Skubala1, Tamura1]. However recent investigations within the Cigre working group WG47 have provided little evidence that failure of transformers with low DP values are as a result of mechanical weakness of the paper [Duval5]. The DP used as a condition monitoring tool is usually measured from furan samples of the oil. This gives an indication of the general state of the cellulose insulation as the paper fibres are distributed within the oil. The disabvantage of this is that localised degradation is not easily identified and may be masked by the high volumes of oil.

Experiments in the laboratory to identify aging characteristics were performed at temperatures above 100 °C due to the shorter reaction times under these conditions [Kachler1]. The aging under normal operating conditions as yet has not been fully investigated. Emsley concluded that at most a ±20% estimated life of transformer paper insulation at normal operating temperatures can be calculated from laboratory experiments with associated statistical errors [Emsley2].

Abu-Siada and Islam introduced a new method using Gene Expression Programming (GEP) to standardise DGA interpretation techniques thus alleviating the need of expert knowledge for fault diagnosis [Abu-Siada1].

Ma et al. introduced the statistical learning techniques and their application for condition assessment of power transformers [Ma1]. This algorithm when compared to the conventional ratio based DGA interpretation methods are able to indicate several fault conditions that may occur simultaneously within a transformer or if the deterioration is due to normal operating conditions.

Jadav et al. presented findings from the analysis of polarisation and depolarisation current mesurements and comparison to dissolved gas analysis [Jadav1]. It was found that although dissolved gas analysis provided useful information about the insulation condition and the presence of the fault within a transformer it appears difficult to quantify the amount of insulation degradation taking place.

It was found that most of the new methods available are usually variations and combinations of the fundamental diagnostic methods as discussed above.

2.6. SUMMARY

Power transformers are generally designed for an operating life of 30 to 35 years. However, depending on how the transformer is operated, maintained and exposed to external risk these values may be less. Over the last 20 years trends have indicated that the transformer life has been much lower than expected. Even within Eskom, from statistics since the early 1990's it was found that the average life of the larger GSU transformers were around 15 years.

A major contribution to transformer failure is windings, leads, tap changer and bushings. These failures are usually catastrophic to the transformer and in most cases the transformer has to be either rewound or replaced.

The two major components of the transformer that have the faster degradation rate are the oil and paper insulation. These components degrade as a result of thermal, electrical and chemical stress. Paper insulation degrades very early with elevated operating temperatures. Chemical stress usually takes a long time to affect transformer health and predominantly affects the oil. Electrical stress is the most destructive and with rapid degrading mechanisms on both oil and paper insulation.

It was clear from the literature thus far that the key components to focus on when assessing transformer health are the oil and cellulose/paper insulation under chemical, thermal and electrical stress.

Chapter three uses these baseline findings to conceptualise the relationship of energy to the degradation mechanisms within the power transformer.

CHAPTER 3

PARAMETER - ENERGY CONCEPT

3.1. INTRODUCTION

Chapter two discussed the current knowledge of the failure mechanisms and components affecting transformer health. The theory provided clear direction on which major transformer components (cellulose and oil) to focus on and the parameters that may provide some indication of the severity and rate of degradation.

This chapter takes these concepts further in developing a parameter-energy model to link the different failure mechanisms to the degradation of the oil and paper insulation within the power transformer and identify which parameters are relevant for the identification of incipient fault conditions.

Different operating and environmental conditions of varying severity affect the transformer lifespan [Emsley1]. Some conditions may have a more significant influence on the transformer life than other conditions and can result in sharply reducing the designed lifespan of the transformer. Yet some conditions may result in the degradation of the transformer components but can be controlled to ensure maximum asset usage.

Clearly identifying these parameters and mechanisms allows for a structured approach to managing transformer risks and asset management thereof. The following section describes a possible model to be used for understanding the impact of each of the degradation mechanisms to the amount of energy released.

3.2. SEVERITY-LIFESPAN (SL) MODEL

The Severity-Lifespan Model (SL) provides a means of evaluating particular transformer risks to enable effective plans to be put in place for condition recovery. Present theory supports the notion that the transformer health is directly related to the condition of the insulation [Cigre WG12.18]. Insulation deterioration can be rapid due to high energy and mechanical forces or slow due to chemical degradation mechanisms. Ageing models relate thermal characteristics as the prime mechanism of insulation ageing yet a significant number of transformers that suddenly fail have not exhibited high elevated temperatures [McNutt1]. The SL Model was created with a specific focus on the holistic conditions that contributed to the transformer health.

The model was based on three levels of impacts. These are long term, medium term and short term impact and the details are captured in figure 3-1.

Severity (Increasing Impact)	Term	Time Frame	Degradation Mechanisms	Causes	Symptoms	Parameters	Detail
	Short Term	***Abnormal Events*** Compromise health within 0-1 Years	System Events	Through Faults	Elevated Temperatures	H_2, CH_4, CO, C_2H_6, C_2H_4	These mechanisms have a significant impact on the life of the transformer. They may result in immediate failure or a trigger of imminent failure of the transformer
				Overvoltages	Discharges	H_2, C_2H_2	
				Inrush Currents	Insulation damage due to mechanical forces	H_2, C_2H_4, C_2H_2	
			Environmental Events	Lightning	Insulation breakdown (HV winding)	H_2, C_2H_2	
				GIC	Localised Hotspots	H_2, CH_4, CO	
		Major Components Compromise health within 1-2 Years	Bushings	Contamination or ageing	Partial Discharge	Low Tan Delta, PD Measurement	Failure of these components can end transformer life especially when subjected to stress such as highlighted above
			Tap Changer	Manufacturing and installation defects. Inadequate maintenance	Loose/stuck contacts/Arcing	H_2, C_2H_4, C_2H_2	
		Controlled Abnormal Events Compromise health within 2-5 Years	Localised Hotspots	Design Defects	Cooling, Stray Flux	H_2, CH_4, C_2H_6, C_2H_6	Design issues may have to be managed if the transformer is already manufactured. Can be identified and rooted out for new transformers in the specification and design reviews process. Overloading must be managed within limits
				Operating Conditions	Elevated temperatures	H_2, CH_4, CO	
				Manufacturing Defects	Bad welding, Earthing &	H_2, CH_4, CO	
			Vibration		Loose Clamping of Windings - PD	H_2	
	Medium Term	Compromise health within 5-10 Years	Pyrolysis (Temperature)	High Hotspot temperatures	Elevated temperatures	H_2, CH_4, CO	Any of these conditions result in starting degradation mechanisms of the insulating material and metal structures. The effects are some what slower and generally builds up over time. Failure can result but in extreme conditions. Such mechanisms can be reduced where it is identified early with adequate steps put in place to stop the processes.
			Oxidation (Cellulose)	High levels of external O_2 and oil acidity with High Temperatures	Formation of Sludge	H_2O, CO_2, Furfurals	
			Corrosive Sulphur	High sulphur levels	Elevated levels of Copper Sulphide	Lower kV and O_2 with elevated temperatures	
	Long Term	Compromise health within 15+ Years	Oil Quality	High Particle Contaminants	Low dielectric Strength of oil	kV, Interfacial Tension	These conditions can be tolerated within limits for long periods but must not get out of control as it will result in the medium term mechanism listed above.
			Hydrolysis (Moisture)	Consistent high levels of moisture	High moisture levels	H_2O	
			Oxidation (Oil)	Tank Leaks Free Breathing	Formation of Sludge	O_2, Acidity	

Figure 3-1: Severity Lifespan Relationship

3.2.1. Long Term Impact

Long term ageing factors of figure 3-1 are those that are present in the transformer but do not significantly affect the transformer life immediately. These may however be catalysts and supporting mechanisms for other more severe degradation processes. These ageing mechanisms are usually contained and originate in the oil medium.

3.2.1.1. Oil Quality

Oil quality is a major aspect of transformer health [Lapworth1]. For oil to carry out the intended functions of dielectric and as a heat transfer medium it needs to be within specification. The following parameters are utilised for oil quality monitoring; dielectric strength, water, acidity and interfacial tension.

Dielectric Strength

All insulating material has some resistance to breakdown. This is measured as dielectric strength and in terms of transformer mineral oil; it is the ability of the oil to withstand electrical stress caused by high voltage gradients [Wang2]. This measure is applied predominantly to the oil giving an indication of its condition due to the dielectric strength being highly affected by contaminants such as water and free particles in the oil. The dielectric strength is measured in kV/2.5mm gap.

Water (H_2O)

Water is one of the major contaminants in a power transformer [Lundgaard1]. It is usually found in the paper insulation or dissolved and as free water in the oil [McNutt1]. Water is always present in an oil-immersed transformer and originates either from the atmosphere or internally from chemical reactions during the degradation process of oil and paper insulation [Garcia1]. Water content in the oil is dynamic as its solubility is highly temperature dependent and migrates between the oil and paper to reach an equilibrium state [Sheiretov1].

Water forms a significant catalyst in the breakdown process of the oil and paper insulation. When left uninfluenced, it creates a sustained cycle of cellulose breakdown and increase in water levels [McNutt1]. Water is measured in parts per million.

Acids

The acidity of the oil originates from chemical reactions due to the degradation of the oil, which is usually as a result of oxidation of the oil and particles and this process is highly sensitive to temperature and levels of oxygen in the oil [Lundgaard1]. With the presence of water, the acidity can affect metal parts like the tank and supporting structures causing corrosion. If the acidity of the oil reaches high proportions, it results in the production of sludge [Gossling1]. Acidity is measured in mg.KOH/g oil.

Interfacial Tension

Interfacial Tension is the measure of tension at the interface between oil and water [Shaban1]. The measuring unit is dynes/cm with good oil having a reading between 40-50 dynes/cm. Both water and by-products of oil oxidation have the effect of reducing the interfacial tension measure [Eklund1].

3.2.1.2.Hydrolysis

Hydrolysis is the decomposition of a chemical compound by reaction with water. [Cigre WG12.18] highlighted that the energy of activation of pyrolysis is 1.4-2.0 times as great as the energy of activation of hydrolysis with hydrolysis being the dominant process for temperatures between 110-120 °C. The hydrolytic process requires an acid catalyst to provide a hydrogen atom to initiate the process [Emsley3].

3.2.1.3.Oxidation of Oil

Oxygen has a strong affinity for electrons and the process of bonding where oxygen consumes electrons from other atoms is oxidation [Sabau1]. This is evident in power transformers especially on the oil and paper insulating material. The oxidation of transformer oil produces acids, aldehydes, ketones, esters and sludge. A mixture of hydrocarbon molecules and particles form sludge [Sabau1].

Summary

Moisture is one of the most significant factors affecting transformer health due to its role played in the breakdown of solid insulation and contribution to reducing the dielectric capability of the insulating medium. Increased moisture levels in the oil reduce both the dielectric strength and interfacial tension capability of the oil medium. Temperature affects the solubility and migration of moisture between paper and oil. Fluctuating temperature thus creates dynamic moisture patterns and new equilibrium levels within the paper and oil. High top oil temperatures cause moisture to migrate from paper to oil.

It is generally found that elevated temperatures with increased levels of moisture and oxygen has the effect of lowering the dielectric strength, interfacial tension of oil with an increase in the quantity of acids.

↑ Temperature, ↑ Moisture, ↑ Oxygen ↑ ⇒ ↓ kV, ↓ IFT, ↑ Acidity

With insulation degradation, the particle count in the oil increases which has the effect of reducing the dielectric strength and interfacial tension of oil with the tendency of bubble formation under steep loading conditions of the transformer [McNutt2].

↑ Particles ⇒ ↓ kV, ↓ IFT ⇒ ↑ Bubble Formation (affected by loading)

The increase in oxygen levels in the transformer results in the increase in the oxidation rate producing higher levels of carbon monoxide, carbon dioxide and acids due to cellulose degradation

↑ O_2 ⇒ ↑ Oxidation ⇒ Produces CO, CO_2, acids

3.2.2. Medium Term Impact

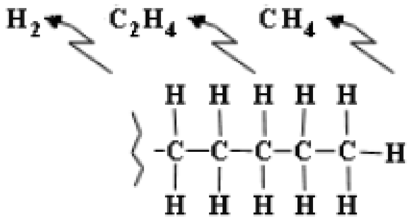
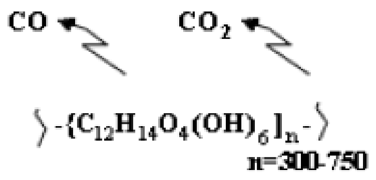
Medium term impact factors of figure 3-1 are composed of degradation processes, which have already been initiated and reaching levels that may reduce the transformer lifespan drastically. These consist of pyrolysis, oxidation of cellulose and the effects of corrosive sulphur. This section identifies methods of how these processes can be effectively measured.

3.2.2.1.Pyrolysis

Pyrolysis may be defined as the chemical decomposition of organic material when heated at high temperatures, usually greater than 300 °C and within 700 °C. One of the key aspects of pyrolysis is that it does not require oxygen or any other reagents [Demirbas1]. The process predominantly yields hydrogen and methane but for extreme cases yields carbon.

DiGiorgio identified relationships of typical fault gas distributions for pyrolysis in oil and of cellulose as highlighted in table 3.1 [DiGiorgio1].

Table 3.1: Typical fault gas distribution for pyrolysis in oil and cellulose [DiGiorgio1]

	Oil	Cellulose
Chemical Reaction		
H_2	16 %	9%
CO_2	Trace	25%
CO	Trace	50%
CH_4	16 %	8%
C_2H_6	6%	
C_2H_4	41%	4%
C_2H_2	Trace	0.3%

Experiments conducted noted that at 700 °C the oil is completely decomposed to form methane, ethane and propane with no traces of acetylene [Buenomak1].

3.2.2.2. Oxidation of Cellulose

Due to cellulose having oxygen as one of its molecular components, it degrades at a faster rate than oil. The oxidation process produces water, carbon dioxide and furfurals [Liland1]. High temperatures and higher levels of oxygen and acidity significantly affect this process, which causes rapid breakdown of the glucose molecules into shorter chains decreasing the overall strength of the paper. Aging of the paper also increases the acidity of the oil [Lundgaard1].

3.2.2.3. Corrosive Sulphur

The formation of copper sulphides in transformers became a problem of note in the late 1990's to present date. This was due to the changes in the methods of refining and oil purification with new suppliers in the transformer oil industry introducing new sources of crude oil having different profiles of naturally occurring sulphurous compounds [Sundin1].

The two mechanisms of copper sulphide are the corrosion of copper and the depositing of copper sulphide on conductors and paper insulation. The effect of this is either a reduction in the dielectric strength of the solid insulation or providing a conductive path [Lewand1]. Significant copper sulphide build-up results in the flaking of these conductive particles in the oil, which reduces the dielectric, and cause related failures [Griffin2].

The corrosive sulphur destructive process is highly temperature dependent. During conditions of low temperature, the process is one of either predominantly the formation of conductive sulphides, which then suddenly results in failure at elevated temperatures, or when the amount of copper sulphide is enough to cause conduction.

This process does not usually result in the production of fault gases and thus failure is unexpected and virtually undetectable. Copper sulphide production has been found to be a localised phenomenon.

Figure 3-2: Copper Rods and Kraft paper insulation after testing [Lewand1]

The Cigre WG A2-32 (Copper sulphide in transformer insulation) has identified the following key aspects of corrosive sulphur in power transformers [Cigre WGA2-32, Dahlund1]:

- Sulphur must be present in the transformer oil. This includes oil types such as naphthenic and paraffinic or intermediate oils.
- Temperature plays an important role in the process but is not the sole factor for occurrence. Copper sulphide formation at temperatures from 80 °C to 150 °C was demonstrated in a laboratory.

- Most failures recorded to date have been found in GSU transformers, shunt reactors and HVDC transformers, which were attributed to the high loading tendency of the equipment.
- Failures recorded were also mainly found in closed units, which may indicate that the presence of oxygen slows down the copper sulphide production process.
- The DGA and the usual oil monitoring parameters like tan δ are not susceptible to the detection of copper sulphide production.
- It is generally found that the deposition of copper sulphide closely relates to the thermal profile in the transformer with typical location at the top of windings.

3.2.3. Short Term Impact

Short term impacts of figure 3-1 are conditions that when experienced will result in failure or initiation of failure of the transformer. These are further broken up into three categories which are controlled defective events, major component failure and defective events.

Short Term Impact are conditions within the transformer that are changing in the current environment with visible effects on the parts of the transformer. These are usually evident in the oil medium where measurements can be easily taken from oil samples. These parameters consist of the **water content, dielectric strength, interfacial tension** and **top oil temperature** of the transformer.

By combining these parameters, an effective indicator can be established on the immediate condition of the transformer insulation medium and control further deterioration to limit medium and long-term impacts.

3.2.3.1. Controlled Defective Events

These events are controllable by the engineers and consist of design, operating conditions and manufacturing of the transformer. Operating conditions cover events such as overloading beyond the capability or close to limits. Transformers in the modern era are pushed to limits especially when utilities are faced with under supply of power. Short time overloading can affect transformer life and the process may be irreversible. Transformer designs can also contribute to the lifespan of the transformer. The transformer must be effectively designed to handle a certain level of short circuits and over voltages. The design of the cooling of the active parts is also another important parameter to be considered. The manufacturing process is another risk area where poor workmanship of important components like the core and windings can result in premature failures.

3.2.3.2. Major Component Failure

Major component failures such as bushings and tap changers can be catastrophic to the life of the transformer. These events usually end the life of the transformer no matter how well the main transformer windings and core is designed and manufactured.

Defective Events

Defective events are system and environmental conditions that can severely affect the transformer. Defective system conditions consist of through faults, line over voltages and inrush currents. Environmental conditions consist of lightning and geomagnetic induced currents caused by solar storms. The nature of these events is such that they pose high levels of mechanical and thermal stress on the transformer electric and magnetic components and may be the one event that either causes failure or initiates failure mechanisms.

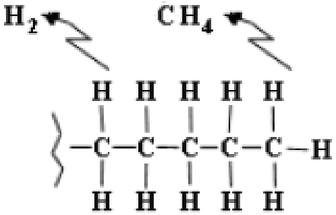
Partial Discharge and Corona

Partial discharge usually occurs within insulation systems that have voids, cracks, and along the boundary between different insulating materials or in bubbles within liquid dielectrics [McNutt2]. Discharges predominantly occur within localised areas with the discharges only partially bridging opposite electrodes [Mathes1].

Partial discharges within the winding paper insulating material are usually initiated within oil-filled voids within the dielectric. This causes the dielectric constant of the void to be significantly lower than the surrounding dielectric, which results in the electric field across the void being considerably higher than across an equivalent distance of dielectric. PD activity usually starts when the voltage stress across the void is increased above the corona inception voltage. The mechanism of deterioration caused by PD is slow and persistent until electrical breakdown occurs within the area [Mathes1].

Table 3.2 below summarises the chemical breakdown and fault gas distribution for typical corona in oil.

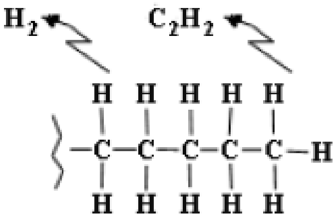
Table 3.2 Typical fault gas distributions for corona in oil [DiGiorgio1]

	Oil
Chemical Reaction	
H_2	88%
CO_2	1%
CO	1%
CH_4	6%
C_2H_6	1
C_2H_4	0.1%
C_2H_2	0.2%

<u>**Arcing**</u>

An electric arc is formed from an electric breakdown of a gas which is able to sustain long enough to cause a current flow through the non-conductive medium [Perkins1]. In the case of a power transformer arcing can occur in the oil (non-conductive medium) between areas of high potential differences. An electric arc is associated with high temperatures that are capable of degrading or destroying the area of the medium around which is forms. The key difference between a partial discharge and an electric arc is that the electric arc results from a continuous discharge of electrons until permanent breakdown occurs [Perkins1]. Typical fault gas distribution for arcing is provided in table 3.3 below.

Table 3.3 Typical fault gas distributions for arcing in oil [DiGiorgio1]

	Oil
Chemical Reaction	
H_2	39%
CO_2	2%
CO	4%
CH_4	10%
C2H_4	6%
C_2H_2	35%

3.2.4. Relevance of Severity-Lifespan Model

The severity–lifespan model is significant in this study as it organises the transformer ageing risks into an integrated chart in relation to the impact and time. The key information from this model is the identification of the insulation degradation mechanisms and how these propagate over time to become catastrophic mechanisms to the life of the transformer. This model also provides a high-level summary of the degradation parameters that would be most effective in identifying the impact of the particular degradation processes.

3.3. ENERGY CONCEPT IN POWER TRANSFORMERS

The first law of thermodynamics states that energy cannot be created nor destroyed but can be changed from one form to another [Perry1]. The transformer is considered to be a system in which a change in the internal energy is equal to the heat added to the system minus the energy lost to the environment. Heat is the energy transferred from one body or system to another due to a difference in temperature. The second law of thermodynamics limits the amount of heat that can be converted into work [Perry1]. The amount of electrical energy in the transformer varies during fluctuations in loading current and during fault conditions.

The migration of heat always occurs from the hotter object to the cooler object. Heat transfer occurs by means of conduction, convection, and radiation . Conduction requires the physical contact of two objects [Kreith1]. In the case of transformer windings, heat is conducted through the layers within the windings from the heat source (conductor - warmer side) to the cooler side that is on the outer surface of the windings, which make contact with the oil. Convection is the transfer of heat due to fluid or air flow [Kreith1]. An example within the transformer is when warm oil rises to the top of the tank where it cools down and then falls to the lower areas, inducing movement or circulation of oil naturally within the transformer. Radiation is the transfer of heat between two bodies that are not in contact by means of wave motion through space [Perry1]. Figure 3-3 provides a representation of the different types of energy sources that may generally exist within a power transformer.

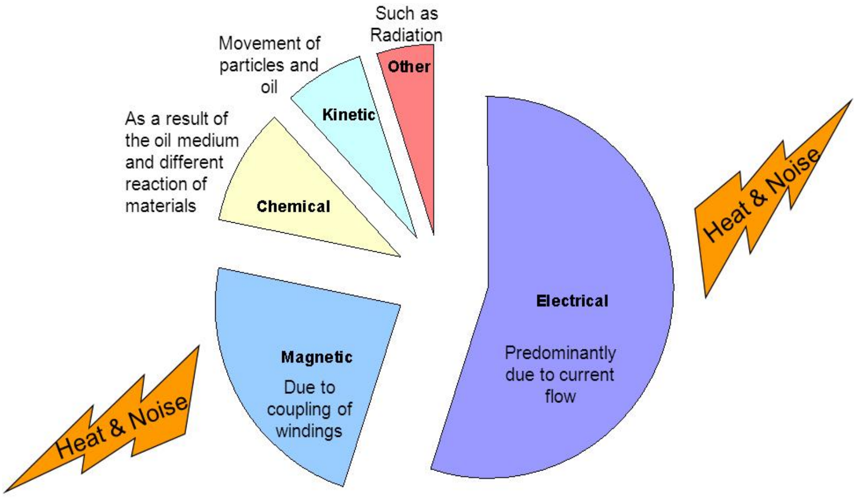


Figure 3-3: Types of Energy in Power Transformers

Power transformers are efficient in transferring power and transforming voltages in power networks with internal real power losses being within 0.5% of the MVA rating at full load [Harlow1]. This means that transformers do release some undesired energy in the form of losses. Leakage inductance is the energy released in the non-magnetic parts surrounding windings usually due to stray flux paths where the temporarily stored energy is proportional to load current squared [Sadati1]. Mutual inductance is the other energy component stored in the finite permeability of the magnetic core and in small gaps where the core halves come together. This stored energy is a function of the volt-seconds per turn applied to the windings, which is independent of load current [Dixon2].

Defective conditions within the transformer can result in the formation of further energy pockets, which initiate stress mechanisms that affect the general health of the internal components.

Asset management requires the assessment of the transformer condition where the identification of energy transfers and releases have the potential to indicate a defective state or insulation degradation. Most transformer failures experienced have been sudden despite there being several fault diagnosis techniques and monitoring systems available.

Transformers are static devices yet numerous problems are experienced due to high stress areas and mechanism within the transformer. The following section provides a detailed summary of these problems related to the associated energy sources within power transformers.

3.3.1. Transformer Losses

During the energy conversion process, losses are experienced within the transformer due to the electrical energy from the source and the magnetic coupling between the primary and secondary windings. The various types of these losses are summarised in figure 3-4. The flow of flux in the steel core sets up some losses in the steel, which take the form of eddy current, and hysteresis losses.

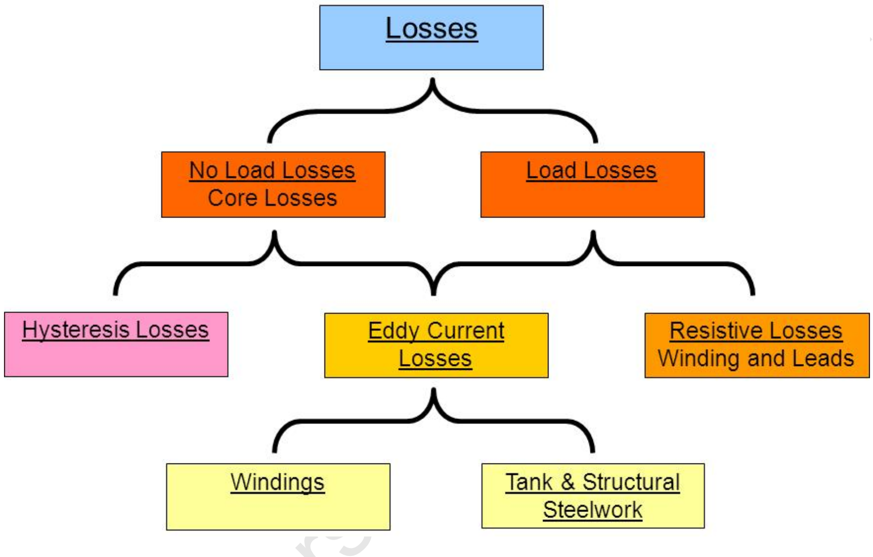


Figure 3-4: Types of Losses in Power Transformers

Each time the magnetic field reverses, a small amount of energy is lost due to hysteresis within the core.

Transformer losses are composed of two major components which are no-load losses and load losses. No-load losses are a consequence of induced voltage in the core whereas load losses are composed of ohmic losses, eddy current and stray losses [Dixon2]. These losses form the basis for transformer efficiency evaluation and provide a foundation for further assessment of the running condition and defective energy sources especially those emanating from stray and eddy current losses.

The flow of load current in the windings of the transformer sets up load losses. Leakage fields within the transformer create circulating currents in the steel laminations, which cause eddy current losses. Leakage flux that intercepts nearby conductive materials such as the transformer support structures gives rise to eddy currents, which converts to heat.

3.3.1.1. Ohmic Losses

Ohmic losses are losses attributed to the windings and arise from the resistance of the winding. The energy released is the product of the current and the resistance. Resistance increases with temperature. The current is not distributed evenly in a conductor because of the magnetic effects even at 50 Hz.

Mitigation - In large transformers, various techniques are used to control the distribution of the current within the conductor, including continuously transposed conductor. Transposition of the strands permits the load current to divide equally among the strands thereby preventing the strands from exposure to varying amounts of leakage flux and different induced voltages [Winders1].

3.3.1.2. Eddy Current Losses

Eddy current losses consist of winding and structural stray losses. The proximity effect is one of the causes of winding eddy current losses and is formed as a result of one current carrying conductor or magnetic fields that induce eddy currents in other conductors which is in close proximity to other current carrying conductors or magnetic fields [Butterworth1]. The further concern of eddy current losses is that it increases approximately with the square of the frequency in the presence of harmonics [CDA Publication 144].

Mitigation – For reducing winding eddy current losses without reducing the turn cross-section the turn conductor is divided into a number of smaller strands individually insulated from each other with transposition [Kulkarni1]. Another method incorporates the use of flux shunts to modify the leakage flux patterns so that these do not pass through the windings or pass through axially.

3.3.1.3. Stray Losses

Stray loss problems are becoming more evident due to the larger sizes of transformers like GSU and furnace type transformers where stray losses due to high current carrying leads result in hot spots [Kulkarni1]. Structural components like the main tank are usually affected due to the size and inadequate shielding. The transformer tank is exposed to stray flux emanating radially from the outer surface of windings causing eddy current losses [Kulkarni1].

Mitigation – Stray losses can be controlled by using smaller dimensioned conductors for windings with transposition for high currents, by utilizing a magnetic shielding on the inner transformer tank walls, using nonmagnetic steel for components exposed to strong magnetic fields or by the positioning of large metallic parts away from strong magnetic fields [Koncar1].

3.3.2. Faults within a Power Transformer

The following faults are listed specifically for transformer internal faults that are relevant to the scope of this study. Faults related to the transformer accessories such as bushings and tap changers do not form part of this investigation.

3.3.2.1. Inter-turn Faults

Inter-turn faults arise as a result of the breakdown of the insulation between strands. This may occur due to ageing, thermal degradation, vibration and partial discharges. The different types of coils are all vulnerable to inter-turn failure and may be defined as crossover, continuous-disc and spiral coils in the order of susceptibility [Kulkarni1, Perry1].

The nature of GSU transformer operation with a direct connection to the high voltage transmission lines at 400 kV and higher makes it more susceptible to steep impulse voltages [GEC1]. Inter-turn faults are recognised by localised burning of the affected conductors, which causes charring of the associated paper insulation [Heathcote1].

Inter-turn faults in the primary winding result in the short circuited turn acting as an autotransformer load on the winding whereas an inter-turn fault on the secondary winding acts as a double winding load [Perry1].

Turn to turn faults can occur both in primary and secondary windings of the transformer. These faults usually start off with insulation degradation between turns which are usually benign at this stage and cannot be picked up by electrical protection due to low current drawn from the line [Kulkarni1]. Further deterioration causes proliferation into more turns and layers resulting in a higher current, low impedance faults [Plummer1, Lunsford1]. It is found that heavy fault currents are generated in the short circuited loops of a few shorted turns but the terminal current remains small due to the high ratio of transformation between the whole winding and the short circuited turns [GEC1].

3.3.2.2. Thermal Faults

Thermal faults are as a result of a build-up of defective energy levels in a contained area or from the transfer of elevated levels of energy across a medium. IEC 60599 defines a thermal fault as an excessive temperature rise in the insulation caused typically by insufficient cooling, excessive circulating currents in adjacent metal parts or through the insulation and overheating of internal winding or bushing connection lead [IEC 60599]. Figure 3-5 provides a mind map representation of possible sources of thermal faults in power transformers.

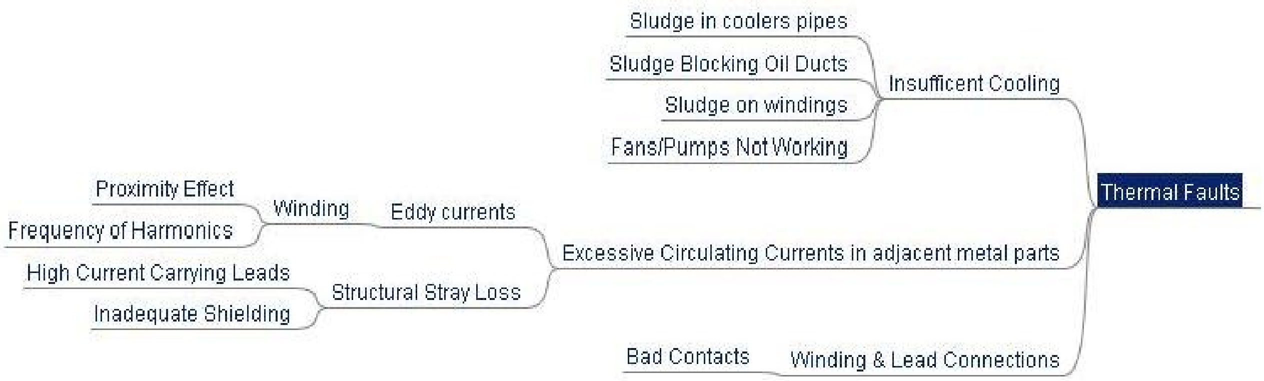


Figure 3-5: Origin of Thermal Faults in Power Transformers

Thermals faults may be classified into low energy and high energy faults which affect the rate of material degradation. Thermal faults cause the insulation medium to break down by elevating chemical degradation processes or by physical changes in the actual material. Low energy faults are composed of partial discharges of the cold plasma (corona) type or of the sparking type, inducing pinhole and carbonized perforations (punctures) in paper [IEC 60599]. High energy faults are composed of thermal faults of temperatures above 700 °C or metal fusion (>1 000 °C) [IEC 60599]. Thermal conditions such as pyrolysis in oil produce significant levels of ethylene and some hydrogen and methane [Wang1].

3.3.2.3. Overloading

Overloading of power transformers beyond the nameplate ratings increases the load current resulting in elevated temperatures in the windings which are transmitted to the paper insulation and oil. Further effects include increases in leakage flux density outside the core with corresponding increases in eddy current heating of nearby metallic parts.

Transformer overloading is a phenomenon used more frequently in the current energy crisis within South Africa. The generating units are pushed to their maximum limits and short time overloading is more evident. Although top oil and winding temperatures are not frequently exceeded, localised hotspots may be evident more often than not. This stress is released in short bursts and its effect on the transformer insulation is slow but permanent. Sudden rise in hotspot temperatures to about 140°C may result in the formation of gas bubbles in the paper insulation thereby reducing the dielectric strength at the high electric stress areas [Perera1]. Gas bubble formation is predominantly dependent on the rate of change of temperature and may occur at lower temperatures for high temperature gradients [McNutt2].

A transformer can be loaded within the limits of the thermal capabilities of the insulating materials. Transformers are designed with temperature rise limits as bound by international specifications such as IEC60076-2 Power Transformers Part 2: Temperature Rise [IEC 60076-2]. Coolers are designed accordingly for each transformer. Over time, the cooling efficiency is reduced or failures may occur in the cooling circuit to reduce the efficiency of the cooling. This directly affects the amount of energy remaining within the transformer thereby affecting the thermal limits and areas where cooling was inadequate even with the designed efficiency.

3.3.2.4. Geomagnetic Induced Currents

Voltages are induced in the transmission network due to fluctuating ionospheric current systems and from the effects of the currents induced in the earth during geomagnetic storms [Boteler1]. These voltages set up geomagnetically induced quasi-dc currents (GIC) in the power transformers of frequency magnitudes less than 1 Hz, duration larger than 1 second and current magnitudes up to and greater than 100 A [Molinski1]. When GICs enter the grounded neutral of star connected power transformer windings it distributes approximately equally among the three phases, biasing the excitation characteristics of the transformer where a low level of amps can drive the transformer into half-cycle saturation [Gish1].

The saturated transformer limb causes most of the excess flux to flow through adjacent paths such as the tank and clamps resulting in associated eddy currents with localized tank wall hotspots in the range up to 175 °C [Kappenman1].

Mitigation - Numerous methods can be incorporated to reduce or eliminate the effects of GIC [Molinski1]. Power transformers on the ends of long transmission lines are more susceptible to the effects of GIC and thus some can be fitted with capacitive devices in the neutral thereby blocking the flow of GIC [Ghalayini1]. Idle transformers in the transmission network can be switched in to either share loading or disperse the GIC thus reducing the heating effect and saturation levels on the transformers. Another aspect of control is the making available of more reactive power (vars) in the network by switching out shunt reactors or by reducing loading of long transmission lines. Another strategy is to prepare or allow the transformer enough margin to absorb the heating effects that may arise from the imminent flow GIC.

All of these mitigation strategies are highly dependent on reliability and accurate monitoring of the onset of geomagnetic phenomena to assist in preparing and providing sufficient time to implement. Other extreme measures can be either switching out critical transformers and circuits thus eliminating GIC effects or by designing new transformers to be able to handle the levels of GIC at the specific point of connection.

3.3.2.5. DC Currents

The flow of defective DC currents within the power transformer as a result of geomagnetic storms, cathodic protection systems and DC operated traction systems can cause saturation of the core. This saturation causes increases in harmonic current flow, heating (of windings, leads and structural components), sound level and vibration of the transformer [IEEE C37.91].

3.3.2.6. Harmonics

Harmonics are a non-linearity of the current or voltage and can be represented mathematically by the components of a Fourier transform, which can assist in understanding the effects. The effect of the distorted current is to increase the resistance and eddy current losses. The effects of the higher frequency components cause heating in the core. Harmonics as a result of current components are more prevalent in power systems which cause additional losses and localized overheating in the windings and structural parts [Winders1].

An increase in harmonic components of the rms value of the load current increases the losses at the square of the current [Dixon2].

Mitigation – One strategy to solve this problem is the selection of the transformer core arrangement. Five legged core form designs allow the two outer legs to act as return residual flux paths around the three core legs between the top and bottom yokes [Winders1].

3.3.3. Operating Conditions

3.3.3.1. Through Faults

Damage to transformers is possible as a result of through faults in the form of thermal and mechanical effects [IEEE C37.91]. External short-circuit events causing severe overloads result in significant increases in the current above rated current, which can result in tremendous forces inside the transformer, together with elevated temperatures in the windings [Kulkarni1].

Mitigation - Proper protection philosophies and settings allows for rapid and correct isolation of the transformers and failure components in the network.

3.3.3.2. Over-fluxing of Transformer

The transformer core is designed to handle a certain level of magnetic flux density beyond which results in the formation of eddy currents within the core and adjacent conductive parts. This can cause rapid overheating of these components with associated damage to insulation. Increasing voltage and decreasing frequency conditions increases the flux levels and overexcites the core, which creates harmonic components (especially 5th) in the exciting current. Specifically on GSU transformers, a sudden unloading during a fault clearing condition or a load rejection scenario may result in ceiling excitation causing over excitation with saturation of the iron core [IEEE C37.91].

Mitigation – These effects can however on most occasions be controlled by proper excitation control (limiters) and protection systems which usually forms part of the main generator protection.

3.3.3.3. Sludging of oil

The deterioration of oil due to ageing and oxidation results in the formation of sludge, which poses a thermal efficiency problem, related both internally and to the external environment. Severe sludge formation forms a coating on the windings, which then acts as a thermal insulating barrier impeding ideal heat transfer from windings into the oil medium. This has the effect of accelerating insulation deterioration due to thermal and chemical degradation.

Sludge particles which get into the oil system ends up blocking oil flow ducts in the winding structure forming hotspot pockets which causes premature paper insulation degradation. Sludge particles can also build up in the cooler circuit reducing the oil flow rates and forming a coating on the inner walls of the cooler fins resulting in lower heat transfer from the oil to the air in the external environment.

Mitigation – Testing of oil for acid components and sludge allows for the identification of severe sludge conditions. Once this condition is established, oil conditioning methods can be incorporated to remove loose particles and early acid compounds preventing the build-up of sludge within the transformer.

3.3.4. Measurement of energy

Transformer faults are predominantly as a result of partial discharge, corona, pyrolysis, and arcing [Ciulavu1]. Other mechanisms include hydrolysis and oxidation. The intensity of energy dissipation varies with the fault type with arcing being the most intense followed by thermal and corona [DiGiorgio1].

3.3.4.1. Hotspot method

The most common method of assessing the energy in the form of heat in the transformer is by recording the top oil and winding temperature, which is the simulated hotspot temperature within the windings. Numerous methods and models have been developed in this field to accurately identify the hot spot temperature.

One aspect of the hotspot temperature concept is that temperatures reaching the elevated levels critical to insulation life (above 110°C), are still based on the average energy within the oil medium. This only allows transformer engineers to have some warning that a thermal problem exists within the transformer and still takes a reactive approach as the problem has already started and developed to a stage of affecting the integrity of the insulation material.

3.3.4.2. Direct Method

A direct method of measuring winding hot spot temperature is by means of point sensing fibre optic sensors [McNutt3]. The operation of these devices is based on the absorption and transmission of light by a semiconductor under varying temperatures. This method is still under development and the decision to install is usually based on a cost benefit analysis due to the complexity, opportunity of installation, reliability due to the number of probes installed, and the cost of implementing such a solution. These probes are generally installed in large critical transformers during the manufacturing process. This method does provide a more accurate reading but is limited by physical location where the temperature profile of the full winding cannot be covered.

3.3.4.3. DGA Method

Another method of evaluating energy levels within power transformers is by means of dissolved gas analysis. The breakdown of oil and paper insulation due to thermal effects can be related to the amount of dissolved gases produced within the power transformer [IEC 60599] and [IEEE C57.104]. The boiling point of transformer oil is in the region if 220-250 °C [Wood1]. This is significant as this process breaks down the oil to release the gaseous components measured as combustible dissolved gases in oil.

During energy conditions such as corona in oil, the gas breakdown consists of a significant level of hydrogen and some levels of methane, ethane, ethylene, acetylene, propane and propylene [Winders1]. As highlighted in [IEEE C57.104] large quantities of hydrogen and methane are produced from the decomposition of mineral oil between 150 °C to 500 °C. Studies have shown that at temperatures below 150°C gases such as hydrogen, methane and ethane start to form and above 150 °C ethylene starts forming at an increasing rate with a decreasing concentration of ethane [Winders1]. Further increase in temperature causes the hydrogen concentration to exceed that of methane with significant levels of ethane and then ethylene forming. Increase in temperature levels thereafter produces significant levels of hydrogen and ethylene with traces of acetylene. At around 600 °C the formation of acetylene starts with the ethylene production peaking and a still increasing methane concentration. Hydrogen production starts becoming significant after 700 °C and continues to increase together with the acetylene concentration.

For thermal conditions such as pyrolysis in oil significant levels of ethylene are produced supported by hydrogen and methane [Wang1]. Arcing in oil causes significant levels of both hydrogen and acetylene to be produced.

At high temperatures, Kraft paper insulating the windings oxidizes to release carbon dioxide, carbon monoxide and water [Winders1]. The relationship:

$$T\ (°C) = 100 \times C_2H_4/C_2H_6 + 150 \qquad (1)$$

was proposed for the temperature range 300 °C to 800 °C to derive the temperature of oil decomposition based on the ratio of ethylene (C2H4) and ethane (C2H6) [Winders1]. This relationship provides some indication of the potential hotspot temperature in the region where oil breakdown takes place. This method however by nature of the parameters is limited to a minimum temperature of 150°C and does not cover for lower energy defects.

3.4. LOW ENERGY DISSOLVED PARAMETERS

Figure 3-6 provides an indication of the gas production rates of the combustible dissolved gases within the oil for increasing temperature. It is noted that hydrogen starts to form at low temperatures and maintains the increasing rate of production even well above 1000°C. It provides some correlation to the amount of energy and the levels of hydrogen produced. It is also noted that both hydrogen and methane start to form at low temperatures where methane reaches a maximum value after which further increases in energy results in a decrease in the production rate due to the chemical reactions of hydrocarbon production favouring the higher bonds like ethane and ethylene.

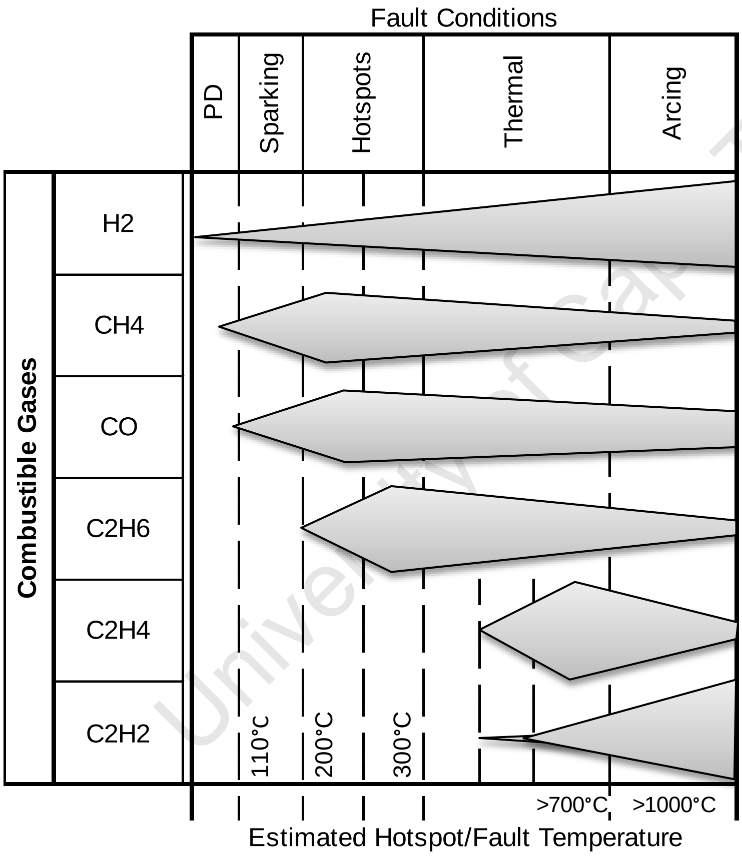


Figure 3-6: Combustible Gas Temperature Production Rates [Duval3, Oommen4]

Figure 3-7 is a diagram as created by Halstead to capture the thermal equilibrium partial pressures as a function of temperatures for the five combustible gases hydrogen, methane, ethane, ethylene and acetylene [IEEE C57.104]. Above temperatures of 725°C, it is found that hydrogen is produced in large quantities and becomes insensitive to temperature. However, for temperatures below 725°C, there is some rate of increase inferring that for temperatures below 226 °C the sensitivity of hydrogen to temperature would be even larger. At about 226°C, methane levels are already at a maximum and thereafter with further increases in temperature; it starts to decrease in value. It is interesting to note that the levels of methane should be higher than hydrogen before they cross over at about 450°C where hydrogen starts to quickly become the dominant of the two gases.

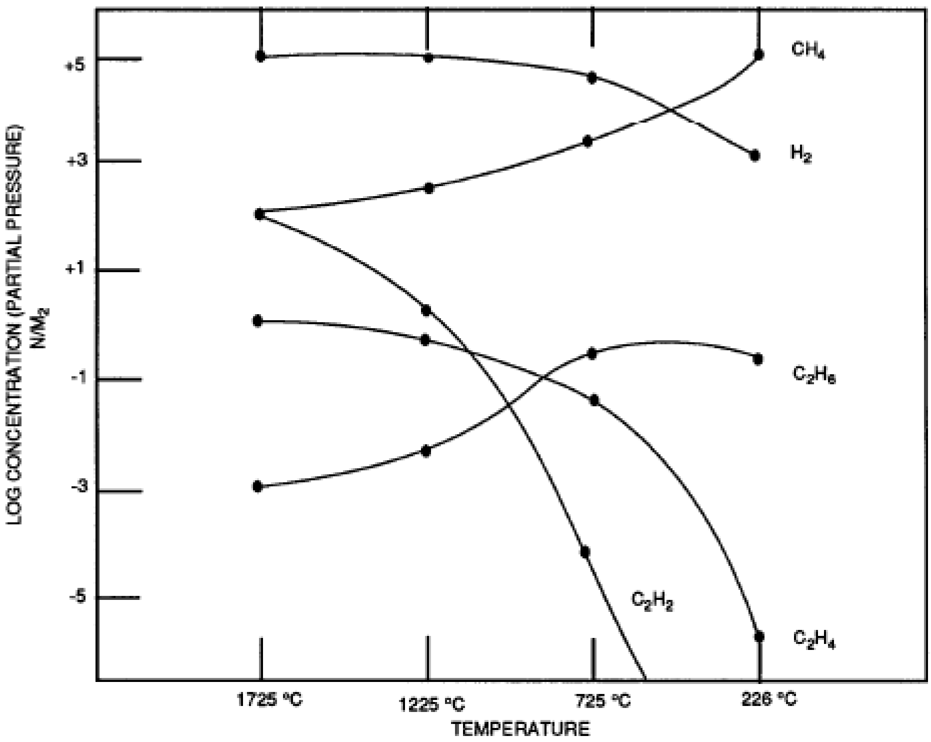


Figure 3-7: Halstead's Thermal Equilibrium Partial Pressures [IEEE C57.104]

Ethane reaches a maximum at around 470°C and the decreases for temperatures higher than 725°C. Ethylene starts to be rapidly produced at temperatures of around 226°C and then rises rapidly to high temperatures. Acetylene levels are most likely to start being prominent at temperatures around 600°C where the rate of production is then high well into the higher temperatures.

From the literature, there are many dissolved parameters as highlighted in column one of figure 3-8. These parameters are generally from dissolved gases and from other dissolved components such as water, acids, particles, furans, corrosive sulphur and silicon. Dissolved parameters are formed predominantly from oil and paper/cellulose degradation. The parameters for oil degradation are hydrocarbons (methane, ethane, ethylene and acetylene), hydrogen, acids, particles and corrosive sulphur. The degradation process of paper produces carbon monoxide, carbon dioxide, water, particles and furans.

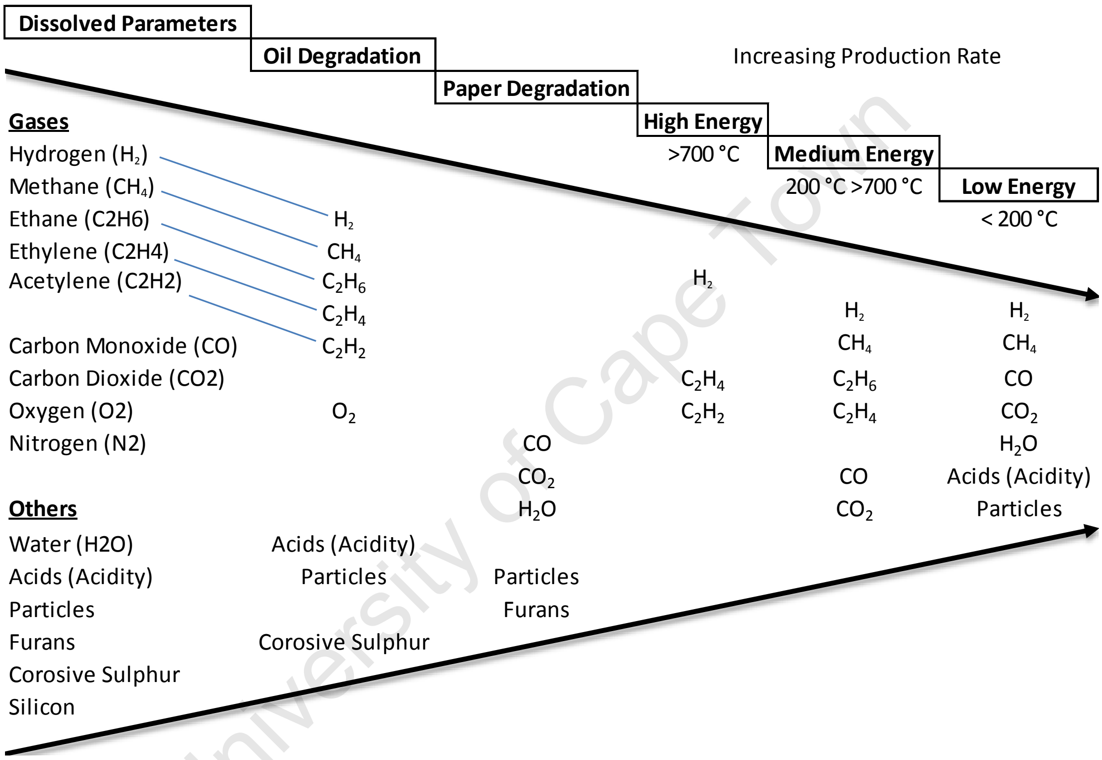


Figure 3-8: Dissolved Parameters

An important aspect of figure 3-8 is the identification of low energy parameters, which are hydrogen, methane, carbon monoxide, carbon dioxide, water, acids and particles. It is also noted that water, acids and particles are not usually dependent on energy and thus may not provide an effective measure of insulation degradation when related to energy. Carbon dioxide may also be absorbed from the external environment. It is envisaged that the three most prominent parameters to be tested in this study are the combustible gases hydrogen, methane and carbon monoxide.

3.5. SUMMARY

Elevated temperatures, pyrolysis, partial discharge and corona, arcing conditions, hydrolysis and oxidation cause the decomposition of oil and paper insulation. However all these degradation mechanisms affect the insulation life in different ways and are clearly described in the severity-lifespan model.

The severity lifespan model categorises the degradation mechanisms into the three health impacts of long, medium and short term.

Many condition-monitoring techniques have been established to monitor the health of the power transformer however the majority of these methods are based on assessing fault conditions or defective conditions that have already manifested. It is thus of extreme importance to identify these problems early enough so that some remedial action can be put in place and to prevent catastrophic failures with associated financial and safety risks.

From the methods of defective energy estimation presented the winding hot spot temperature does give some indication of a general high energy fault but is not sensitive to localized or low energy thermal fault mechanisms. The dissolved gas analysis method offers some variation to localized hot spot estimation as it is related to the immediate effects (material breakdown) of the fault mechanism and location.

Energy plays a major role in the life of a power transformer. The higher the efficiency in transferring this energy out of the transformer and its components the longer will be its economic life. Due to the nature of construction and operation, a transformer is exposed to many conditions that result in the dissipation of some of the load energy in localised areas within the power transformer. It is important to identify these defective conditions as soon as possible so as to be able to either eradicate or reduce the associated effects. Techniques must be established to make such distinctions.

It is concluded that dissolved gases can be utilised to form some relation to the energy levels within the transformer especially the three gases hydrogen, methane and carbon monoxide.

The conclusions identified in this chapter now enable the formulation of a low energy degradation model, which is further investigated in detail in chapter 4.

CHAPTER 4

LOW ENERGY DEGRADATION TRIANGLE (LEDT)

4.1. INTRODUCTION

Both chapters 2 and 3 have now provided the necessary foundation of the theory required for the development of a low energy model to assess degradation of the transformer insulation. Chapter 3 more specifically defined the parameters that are usually by-products of low energy degradation.

Chapter 4 now focuses on the development of the Low Energy Degradation Triangle.

4.2. THREE MAIN DISSOLVED GASES USED IN STUDY

The three main dissolved gases focused in this study is hydrogen, methane and carbon monoxide. The main reason for selecting these combustible gases is due to their prevalence for low energy faults as highlighted in figure 3-8, with methane and carbon monoxide becoming less significant as the fault temperature increases. Further discussion around the characteristics of these gases is discussed below.

4.2.1. Hydrogen (H_2)

Hydrogen is produced throughout the fault energy range within the power transformer. Initial partial discharges produce primarily hydrogen gas as the result of mineral oil breakdown. Thereafter the intensity of hydrogen gas level increases steadily and directly related to the fault energy in the transformer [Mehta1].

4.2.2. Methane (CH_4)

Methane is produced predominantly as the result of the breakdown of oil. It is related to thermal breakdown of the oil at relatively low temperatures in the range 90°C – 500°C. As the fault energy range increases the level of methane initially increases and then reaches a maximum, before declining with further increases in fault energy.

4.2.3. Carbon Monoxide (CO)

Studies have shown that the thermal decomposition of cellulose insulation produces carbon oxides (CO and CO_2) some hydrogen and methane due to the oil impregnation [Kachler1, Wang1]. Other studies have confirmed that CO and CO_2 evolution is related to the thermal breakdown of paper at moderate temperatures in the range 110°C – 700°C and can be directly associated to the remaining strength of insulating paper [Hino1, Hino2, Saito1, Saito2, Yoshida1]. It was found that as the fault energy range increased, the level of carbon monoxide initially increased and then reached a maximum, before declining with further increases in fault energy [Duval3].

Pyrolysis of the paper insulation produces significant amounts of carbon monoxide and carbon dioxide [Demirbas1]. At high temperatures there is a tendency for cellulose to oxidise, forming carbon monoxide, carbon dioxide and water [Winders1]. It is identified that the minimum energy required to cause the incipient carbonizing in the cellulose (heating over 3000°C) is estimated at 0.1 J with an average rate of gas generation under the effect of stable PDs in oil at 50 µl/J [Lokhanin1].

4.3. ENERGY TRIANGLE CONCEPT

It is found that H_2 increases with increasing energy. CH_4 starts to develop early from oil degradation. CH_4 however, due to chemical bonding, at higher temperatures start to decrease in percentage formation. CO starts to develop early from paper degradation. CO also, due to chemical bonding, starts to decrease with higher temperatures.

In a power transformer due to the breakdown of oil and paper carbon oxides and hydrocarbons are produced. Due to the paper breaking down at much lower temperatures than the oil, the CO levels tend to be higher than the H_2 and CH_4 at these temperatures (usually at operating temperatures below 110°C). The hypothesis that these three dissolved gases can provide some indication of the insulation degradation is tested. Thus the combination of these three gases in a triangular plot enables the interdependent relationship to exist. For lower temperatures the CO values are high and the H_2 and CH_4 are low. For moderate temperatures both H_2 and CH_4 tend to be higher than CO. For high temperatures H_2 tends to be the dominant gas. As long as there is oil and paper insulation with elevated energy levels (temperature) this theory should hold true due to the chemical nature of cellulose and hydrocarbon oil.

The proposed three dissolved gases (hydrogen, methane and carbon monoxide) are plotted as a triangular plot on an XY plane similar to Duval triangle [Moodley2]. These three dissolved gases form the sides of the triangle and are represented as percentages having a summation of 100%. Each side of the triangle has a zero starting point vertex reaching 100 % on the far side. Movement along the triangular plot is clockwise for each of the three parameters. Figure 4-1 provides an indication of the general layout of the triangular plot where for further reference the starting vertex on the left is denoted as point O, top apex is denoted as point M and the right vertex is denoted as point H.

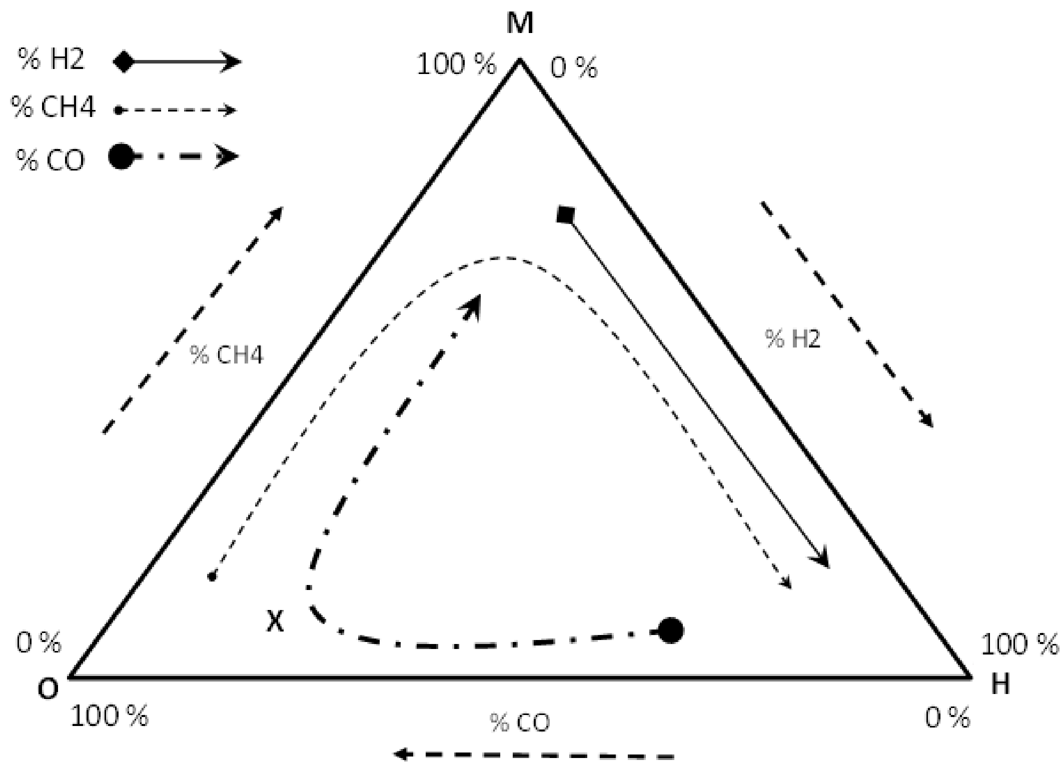


Figure 4-1: Low Energy Degradation Triangle Concept [Moodley2]

For example if hydrogen is 40 ppm, methane 10 ppm and carbon monoxide is 150 ppm the sum is 200 ppm which is equivalent to 100%. The composition of hydrogen is 20%, methane 5% and carbon monoxide 75%. This is plotted as point X in figure 4-1.

Hydrogen levels increase steadily over the fault range implying that the level of energy also increases with increasing hydrogen. With increasing fault energy, and depending on the involvement of oil and paper, the levels of methane and carbon monoxide also increase but then start to decrease for higher energy levels. For medium energy conditions, all three parameters are in the range 30-40% thus the point of intersection is located in the region at the centre of the triangle. Low energy conditions mean low levels of methane and hydrogen with some carbon monoxide thus the values are focused on the lower left side of the triangle. Extremely high energy conditions as a result of arcing conditions usually imply high levels of hydrogen with decreased levels of methane and carbon monoxide such that the intersect points are focused on the lower right hand side of the triangle. More specific conditions and locations are explored further with empirical evidence.

4.4. IDENTIFICATION OF REGIONS

The important aspect of the Low Energy Degradation Triangle is that it offers a visual trend of deteriorating insulation condition. During the preliminary analysis of data, a few prominent regions were identified. These are explained below with reference to figure 4-2.

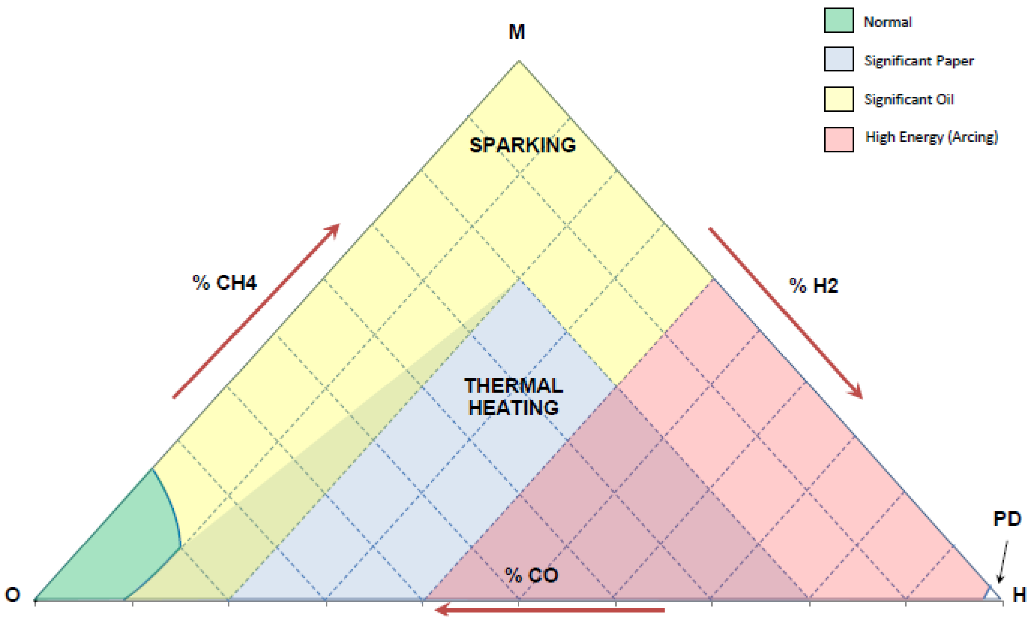


Figure 4-2: Low Energy Degradation Triangle - Regions

4.4.1. Normal

During the operation of the transformer there is some heat generated due to the losses within the transformer, thus there will be some paper and oil affected. This usually results in the generation of small amounts of hydrogen and methane with moderate amounts of carbon dioxide and carbon monoxide. As the fault temperature increases in the region of the paper insulation the levels of carbon monoxide tend to increase at a fast rate which becomes a dominant parameter [Pahlavanpour1].

The significant levels of hydrogen and methane are considered to be around 10% with 80% carbon monoxide.

All values meeting these requirements will fall into a region indicative of a “normal” state. This would mean that the upper limit of normal operation would be governed by the thermal capabilities of the paper insulation that should not exceed 110°C.

4.4.2. Partial Discharge (PD) & Corona

Partial discharges (PD) are usually the starting point of a major insulation break down in power transformer paper insulation. PD occurs when the electric field in localised areas causes an intermittent insulation break down to allow an intermittent flow in the current. There are generally three types of PD, which are voids, corona from sharp edges or floating components and surface tracking. PD due to the floating components and sharp edges give rise to the hydrogen and methane content in the insulating oil [Samsudin1].

Studies concluded that for temperatures at 160°C, PD values are higher when compared to temperatures around 120°C and 140°C, which is indicative that the influence of thermal stress on the degradation of insulation is higher in comparison to electrical stress. This study also found that increase in PD levels resulted in increases in hydrogen concentration in oil [Verma1].

Thus, high concentrations of hydrogen levels with low levels of methane and carbon monoxide may be indicative of a consistent PD source in the transformer. The upper limit of 98% composition of hydrogen is investigated as the limiting factor. This region is indicated in the lower right apex H of the LEDT.

Corona is a low-energy electrical fault. Low-energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Comparable amounts of carbon monoxide and carbon dioxide may result from discharge in cellulose.

4.4.3. Sparking

Sparking is intermittent high voltage flashovers without high current flow resulting in increased levels of methane and ethane without concurrent increases in acetylene, ethylene or hydrogen [Chaudhari1]. This region is indicated in the top apex M of the LEDT.

4.4.4. Thermal Heating

Overheating in the transformer is characteristic of the production of methane and ethylene with smaller quantities of hydrogen and ethane. There may be traces of acetylene for severe cases of overheating where electrical contacts may be involved [Chaudhari1].

Where cellulose insulation is involved significant quantities of carbon dioxide and carbon monoxide are formed. The paper insulation is usually impregnated with oil so there will be some traces of methane and ethylene, depending on the level of thermal energy involved. This region is indicated in the centre area of the LEDT.

4.4.5. High Energy

Arcing is a mechanism of high energy faults producing significant amounts of hydrogen and acetylene with small quantities of methane and ethylene. Due to the presence high currents, high temperatures are experienced. The high energy region is represented by the area coloured in pink. It was observed that for H_2 levels of 40% and higher there was significant levels of ethylene and acetylene which was indicative of high energy arcing.

4.4.6. Significant Paper

Where paper insulation was involved there was significant amounts of carbon dioxide and carbon monoxide produced. From initial analysis of failed transformers with winding failures it was observed that CO where levels between 20-80% with significant levels of H_2 and CH_4. This region is represented by the blue area in figure 2.

4.4.7. Significant Oil

Oil degradation was generally present in all the samples taken. This was due to the oil being present in all areas of the transformer internals especially the paper insulation. It was found that areas where there was significant levels of CH_4 with low levels of H_2 there was evidence of sparking in the oil. This region is represented by the yellow shaded area and usually overlaps with the blue area (significant paper) in the thermal heating region.

4.4.8. Increase along CH_4

Figure 4-3 depicts the region where there is an upward trend of the points along the O-M axis. This would imply that the percentage H_2 is constant, with a steady increase in percentage CH_4 and a relative decrease in percentage CO. This could also imply that the level of percentage CO remains constant with a slight increase in percentage H_2 and a significant increase in percentage CH_4.

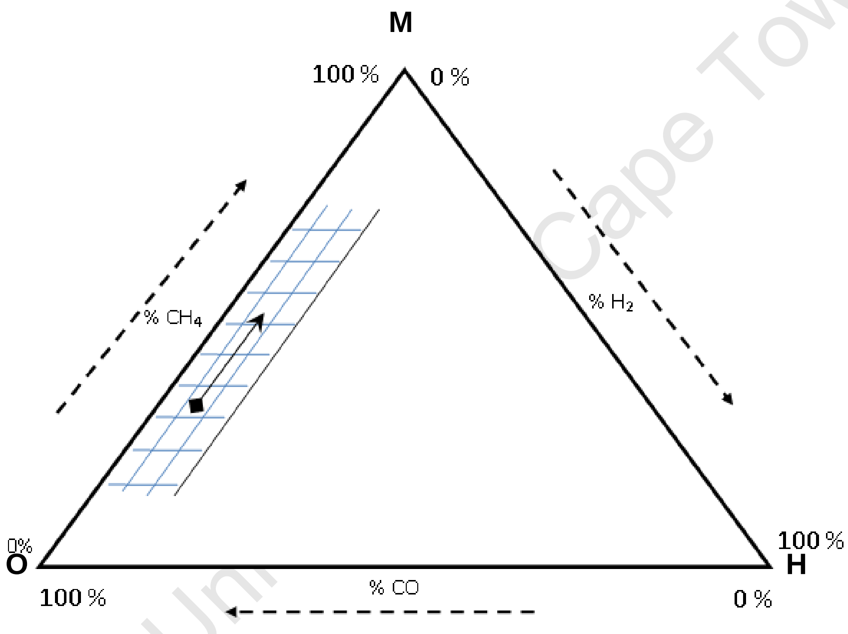


Figure 4-3: Movement along Axis O-M

The significant combustible gas in this case would be methane indicating the significant degradation of mineral oil. Due to the percentage of hydrogen also not having an increasing rate, it may be indicative that the energy involved in this degradation process is constant and not increasing.

4.4.9. Increase along CO

For increases along the O-H as represented in figure 4-4, $\%CH_4$ is fairly constant and low, with an increase in $\%H_2$ and a relative decrease in %CO. This may signify a high production rate of hydrogen with no increase in carbon monoxide and some increase in methane. The increase in hydrogen may signify a high energy condition.

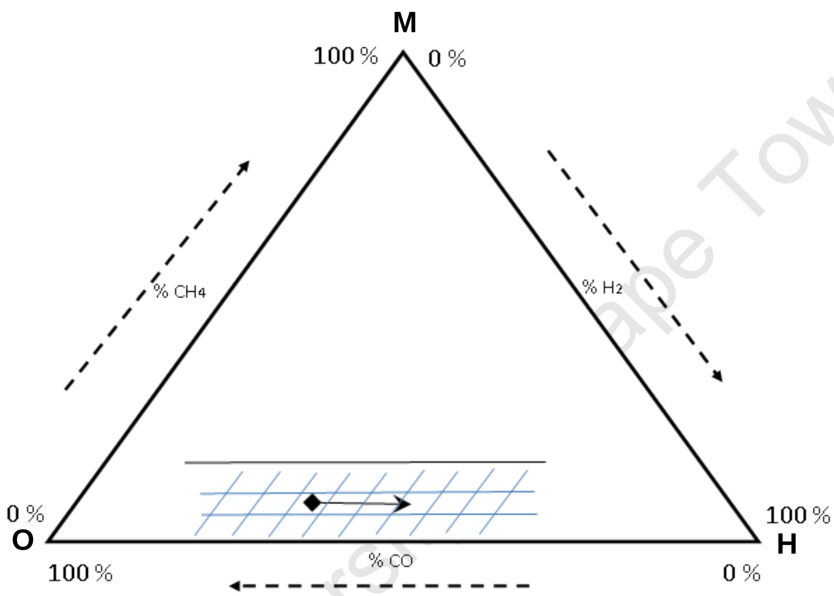


Figure 4-4: Movement along Axis O-H

4.4.10. Diagonal Increase (right)

For diagonal increases to the right as represented in figure 4-5, there is an increase in $\%CH_4$ and moderate increase in $\%H_2$ with decreasing %CO levels. This can signify an increasing energy condition with oil involvement.

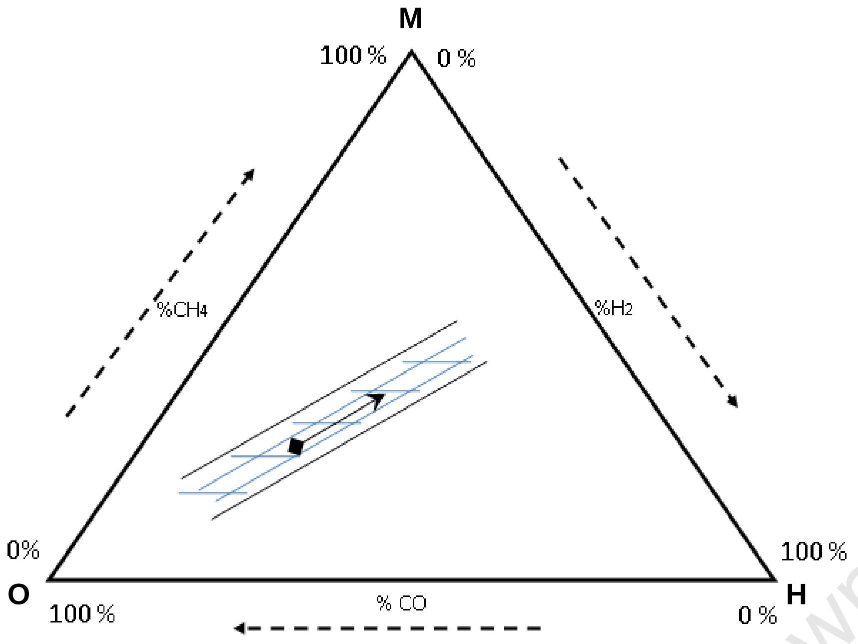


Figure 4-5: Movement - Diagonally Increase (Right)

4.5. TYPICAL MOVEMENT

The following section identifies the typical movement that a transformer may follow during its life cycle.

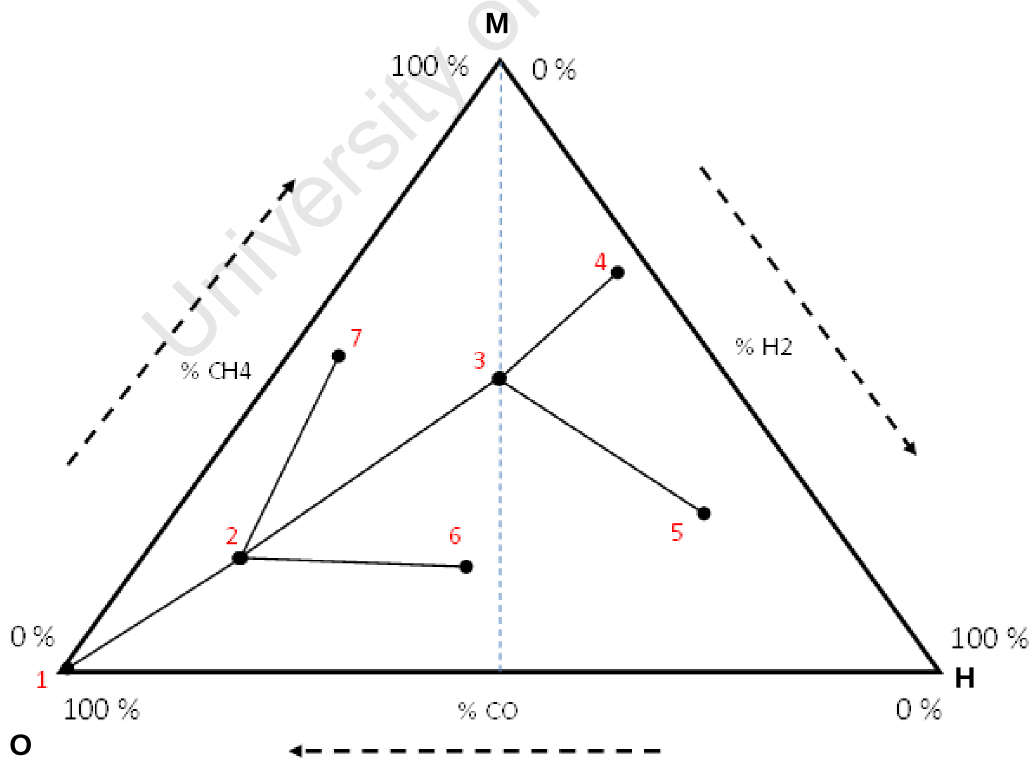


Figure 4-6: Typical Trends within LEDT

Movement from point 1 to 2

When a power transformer changes state from point 1 to 2 there is an indication that:

- H_2 levels have increased. There is an increase in the fault energy at the location of the potential fault.
- CH_4 levels have increased indicating the influence of oil around the area of high energy.
- CO levels have decreased in proportion to H_2 and CH_4

The transformer is starting to indicate that there is energy degradation taking place.

Movement from point 2 to 3

The condition worsens to a high thermal degradation state. Failure mechanisms are imminent:

- H_2 Further increase in levels. Fault energy is increasing significantly. Thermal faults may be present.
- CH_4 Significant increase in levels. Oil degradation may be significant.
- CO proportion has drastically decreased due to significant increase in the percentage of H_2 and CH_4

Movement from point 3 to 4

The condition is bad. Failure may be imminent:

- Percentage increase in H_2 is at a slower rate.
- CH_4 - Significant increase in levels to peak.
- Significant decrease in the rate of CO proportion

Movement from point 3 to 5

The condition is critical if failure has not already occurred:

- Significant increase in percentage of H_2
- CH_4 levels decrease with corresponding increase in H_2 which may be indicative of a high energy fault.
- Significant decrease in the rate of CO proportion

Movement from point 2 to 6

The condition is bad. Failure mechanisms may be imminent:

- H_2 level increases significantly
- CH_4 level is fairly constant indicating a low oil involvement
- CO levels decrease significantly where there may be no increase in the rate of CO production

Movement from point 2 to 7

The condition worsens.

- The H2 level remains constant
- Significant increase in CH_4 level indicating oil involvement.
- CO levels decrease significantly supporting the notion that the fault is in the oil.

This situation is indicative of sparking in oil. The energy released is relatively low with significant oil breakdown.

4.6. IEEE CONDITIONS

The [IEEE C57.104], IEEE Guide for the Interpretation of Gases, identifies four conditions based on the various dissolved gas concentrations. Figure 4-7 provides a dissolved gas concentration guideline as identified within IEEE.

Table 1— Dissolved Gas Concentrations

Status	Dissolved Key Gas Concentration Limits (ppm*)							
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG†
Condition 1	100	120	35	50	65	350	2500	720
Condition 2	101–700	121–400	36–50	51–100	66–100	351–570	2500–4000	721–1920
Condition 3	701–1800	401–1000	51–80	101–200	101–150	571–1400	4001–10000	1921–4630
Condition 4	>1800	>1000	>80	>200	>150	>1400	>10000	>4630

NOTES:
1 — Table 1 assumes that no previous tests on the transformer for dissolved gas analysis have been made or that no recent history exists. If a previous analysis exists, it should be reviewed to determine if the situation is stable or unstable. Refer to Tables 2 and 3 for appropriate action(s) tb be taken.
2 — An ASTM round robin indicated variability in gas analysis between labs. This should be considered when having gas analysis made by different labs.

*The numbers shown in Table 1 are in parts of gas per million parts of oil (ppm) volumetrically and are based on a large power transformer with several thousand gallons of oil. With a smaller oil volume, the same volume of gas will give a higher gas concentration. Small distribution transformers and voltage regulators may contain combustible gases because of the operation of internal expulsion fuses or load break switches. The status codes in Table 1 are also not applicable to other apparatus in which load break switches operate under oil.
†The TDCG value does not include CO_2, which is not a combustible gas.

Figure 4-7: IEEE C57.104 Dissolved Gas Concentrations

Table 1 of IEEE C57.104 although applied using the TDCG or the highest level of individual gases, it is used in this study as a comparison to provide some initial reference of where the generally accepted gas limits for the three gases H_2, CH_4 and CO would lie within the LEDT.

4.6.1. IEEE Condition 1

IEEE condition 1 in figure 4-8 displays dissolved gas concentrations below which the transformer is operating satisfactorily where any individual gas exceeding the individual limits requires more investigation. The upper limit value for H_2 is 100 ppm; CH_4 is 120 ppm and CO being 350 ppm. Using these values in the energy triangle the respective percentages are H_2 17.54%, CH_4 21.05% and CO 61.40%. These values are plotted in Figure 4-8. The blue shaded region meets the criteria for H_2 and CH_4. The green shaded area is within the H_2 and CO limits but is above the CH_4 limit. The orange shaded area is within the CO and CH_4 limit but is outside the H_2 limit.

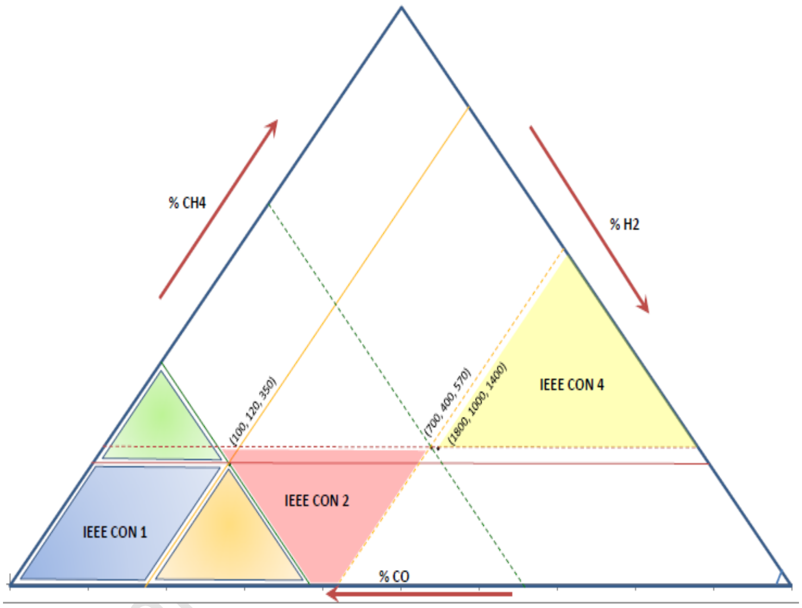


Figure 4-8: IEEE Conditions

4.6.2. IEEE Condition 2

For the IEEE condition 2 the upper values for H_2 are 700 ppm, CH_4 is 400 ppm and CO is 570 ppm. Using these values in the energy triangle the respective percentages are H_2 41.92%, CH_4 23.95% and CO 34.13%.

Figure 4-8 indicates condition 2 by means of dashed lines. The area shaded in pink is where condition two is satisfied for H_2 and CH_4.

4.6.3. IEEE Condition 3

For condition 3 the upper values for H_2 is 1800 ppm, CH_4 is 1000 ppm and CO is 1400 ppm. Using these values in the energy triangle the respective percentages are H_2 42.85%, CH_4 23.81% and CO 33.33%. These values are however not that much different from condition 2 values and are almost superimposed on the triangular plot in figure 4-8.

4.6.4. IEEE Condition 4

IEEE condition 4 is basically values exceeding the limits of condition 3 and is indicative of a highly destructive state where failure is imminent if haven't occurred already.

4.6.5. IEEE condition Boundary

The boundary of each of the conditions was identified as highlighted in figure 4-9. It is observed that there is significant overlap between condition 2 and 3.

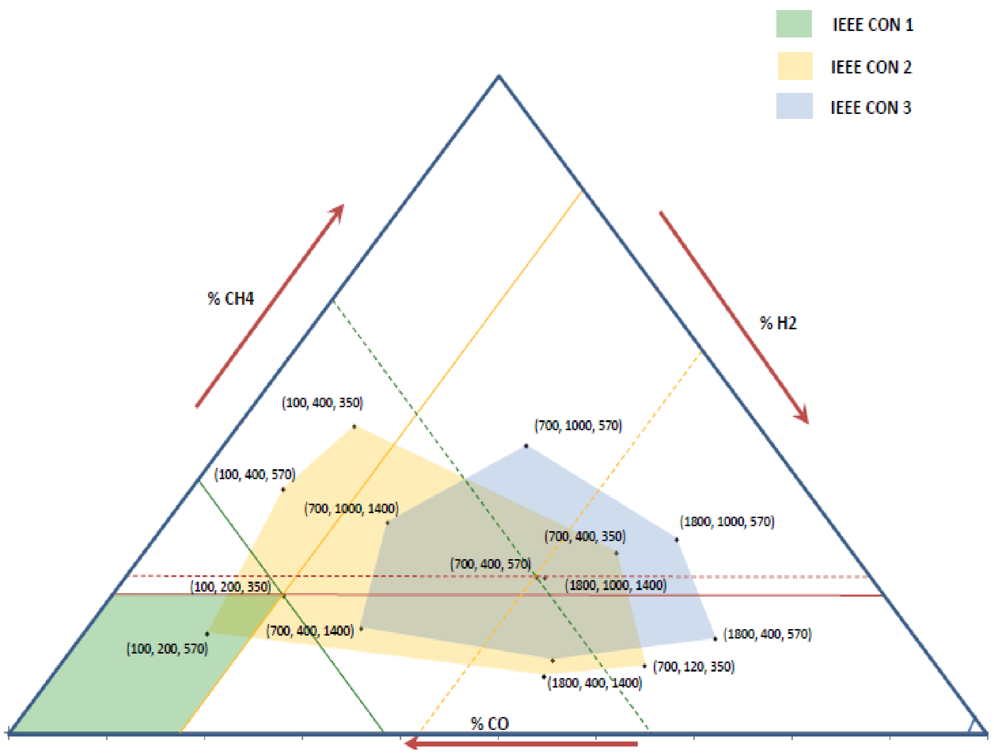


Figure 4-9: IEEE Boundary Conditions

4.7. SUMMARY

This chapter establishes the concepts and development of the Low Energy Degradation Triangle. The three gases hydrogen, methane and carbon monoxide were plotted as a triangular plot on an XY plane. By having such a configuration it is found that as a result of the degradation of paper and oil, for normal operating conditions of the transformers, a profile of normal state is on the lower left corner of the triangle. As the rate of degradation increases there is a tendency of movement towards the middle region of the triangle due to higher levels of hydrogen and methane production.

A brief comparison is made to the limits as set by IEEE for the elevated levels of the three gases and these regions were mapped in the Low Energy Degradation Triangle forming some correlation to the defective state to that of the abnormal condition as presented by the IEEE limits.

Chapter 5 takes an advanced approach to the Low Energy Degradation Triangle to establish the specific relationships between the level of degradation and the amount of energy at the source of the problem. This is used for further refinement of the model as an assessment of transformer health status.

CHAPTER 5

LEDT AS A DEGRADATION – ENERGY MODEL

5.1. INTRODUCTION

Chapter 4 formulated the Low Energy Degradation Triangle and the basic concepts as applied from the theory of transformer insulation degradation. The basic regions of normal and defective state are identified with specific regions and trends within the triangle.

The fault energy is a key component when assessing transformer health. The oil and paper insulation operate under specific design limits to ensure long term sustainability of operating properties. Different fault types exhibit different intensity of energy release within the transformer with increasing order from partial discharge, corona, thermal and electrical (arcing) [Digiorgio1]. Further advanced concepts are now investigated and developed in chapter 5, which focuses on establishing specific relationships for the level of degradation, and the amount of energy involved in the degradation process.

5.2. CONCEPT

Based on the predication that dissolved combustible gases are produced in type and quantity according to the energy at the source it is prudent to explore a model to capture such a relationship based on empirical data. This study has summarised the literature supporting this theory in chapter 3. The gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2 and CO are produced at different temperature levels and are related to the degradation of oil and paper insulation.

The three components of the Low Energy Degradation Triangle H_2, CH_4 and CO are sensitive to temperature by the nature of the chemical degradation process of oil and paper insulation. It is thus hypothesised that every point on the triangle is representative of a unique state of degradation and energy (temperature) that is inherently captured in the production rate of H_2, CH_4 and CO.

5.2.1. Normal Operating State

The triangle point where both H_2 and CH_4 are 0% and CO 100% represented by the XY coordinate (X_0, Y_0) is taken as the origin O for the normal operating state of the transformer (See figure 5.1). This point may be representative of the minimum operating temperature, which is the ambient temperature, plus the temperature rise due to normal losses.

5.2.2. Defective State Progression

The defective state or fault progression within the LEDT is usually towards the centre of the triangle. It is also observed that each point progressing towards the centre is also influenced by the gradient of the path (See figure 5-1).

The amount of fault energy present may correlate with the amount of H_2 gas generated. Increase in %H_2 causes the points to move (from point B to point C) towards the bottom point H of the triangle. This area may be indicative of arcing conditions where the amount of energy is also increasing accordingly with the gradient of the line decreasing.

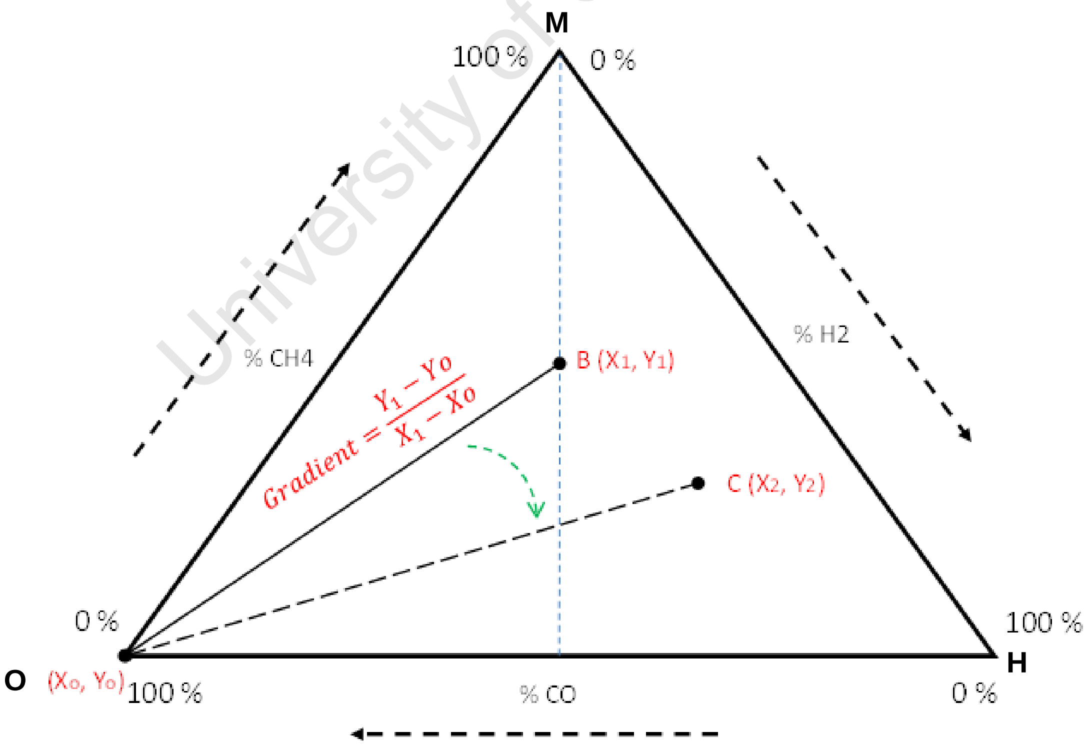


Figure 5-1: Different Points with Varying Gradients

5.3. POLAR PLOT REPRESENTATION

Each of the points on the LEDT is represented by an XY coordinate allowing for each point to have a unique position away from the origin (point O) with a corresponding angle θ.

The distance from the origin thus becomes an important length that can represent the level of degradation of the insulation medium (oil and/or paper) and the gradient or angle θ, the amount of energy causing this degradation. Another method of representing this distance with gradient is by making use of the polar plot concept.

Polar coordinates (r, θ) in the XY plane (figure 5-2) provide a distance from the origin as represented by r. The angle of r (Theta) is the measure of the angle in standard position measured counterclockwise from the X axis.

The position of a point B in this plane is described as its distance r from the origin (point O) and is called the pole where in this case θ Є [0, π/3] is the counterclockwise angle.

The x y coordinates form a right angled triangle such that the following characteristic relationships are formed:

$$x = r \cos \theta \qquad [1]$$

$$y = r \sin \theta \qquad [2]$$

$$r^2 = x^2 + y^2 \qquad [3]$$

$$\tan \theta = y/x \quad \text{or} \quad \theta = \tan^{-1}(y/x) \qquad [4]$$

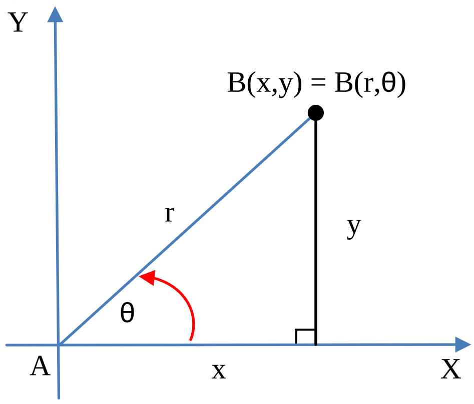


Figure 5-2: Polar Plot

Figure 5.3 indicates the polar plot within the LEDT.

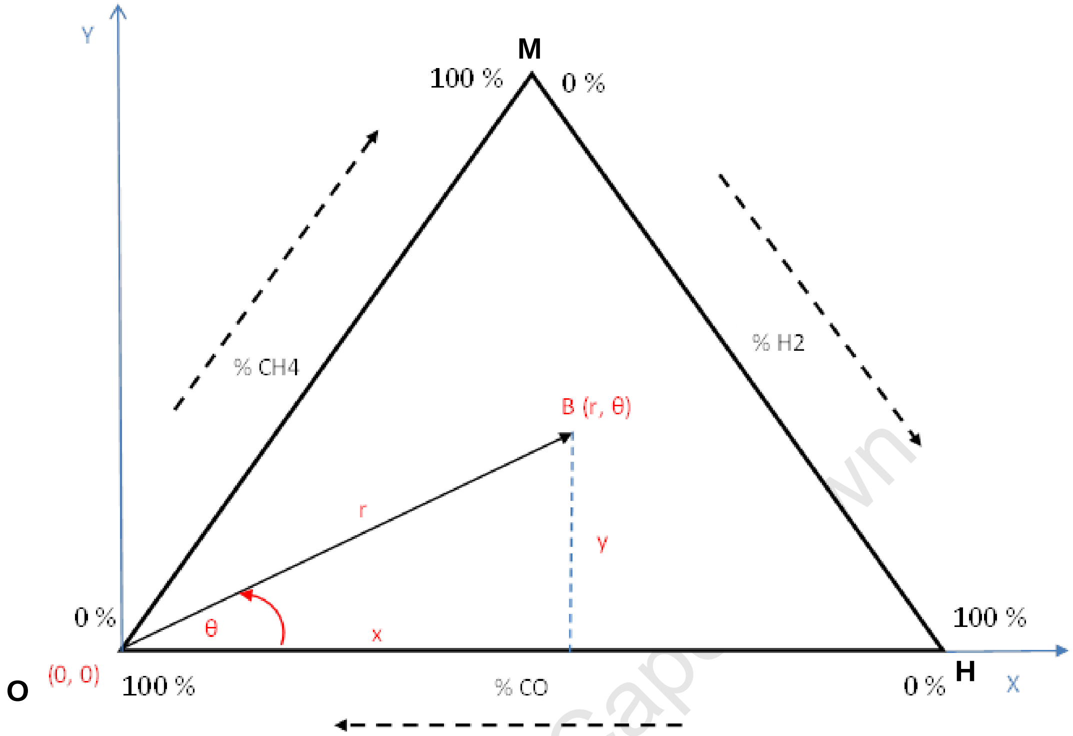


Figure 5-3: LEDT in Polar Plot

5.3.1. Boundary for Normal Temperature

The LEDT detects movement from normal to defective state. Theory states that paper insulation deteriorates rapidly for temperatures in excess of 110 °C and has been an operating limit especially for winding temperature [IEEE C57.91, Lachman1]. Thus at this boundary the temperature limit is 110°C. In terms of the polar plot this temperature may correspond with a specific (r, θ) value.

From the empirical formulation of the LEDT the normal state of a transformer is within the limits 10% of H2, 10% of CH4 and 80% of CO. The XY coordinates (0.15, 0.0866) as per the LEDT coordinates give this point. The corresponding polar coordinates are:

$$r = \sqrt{x^2 + y^2} = \sqrt{0.15^2 + 0.0866^2} = 0.1732$$

With $\theta = \tan^{-1} y/x = 30°$

The value of r = 0.1732 can be representative of the level of degradation as would be experienced at a temperature of 110 °C. The polar region given by r = 0.1732 would be indicative of a circle with radius r. In the case of the LEDT angle θ is limited within the range $0 < \theta < 60°$ ($\pi/3$) as indicated in figure 5.4.

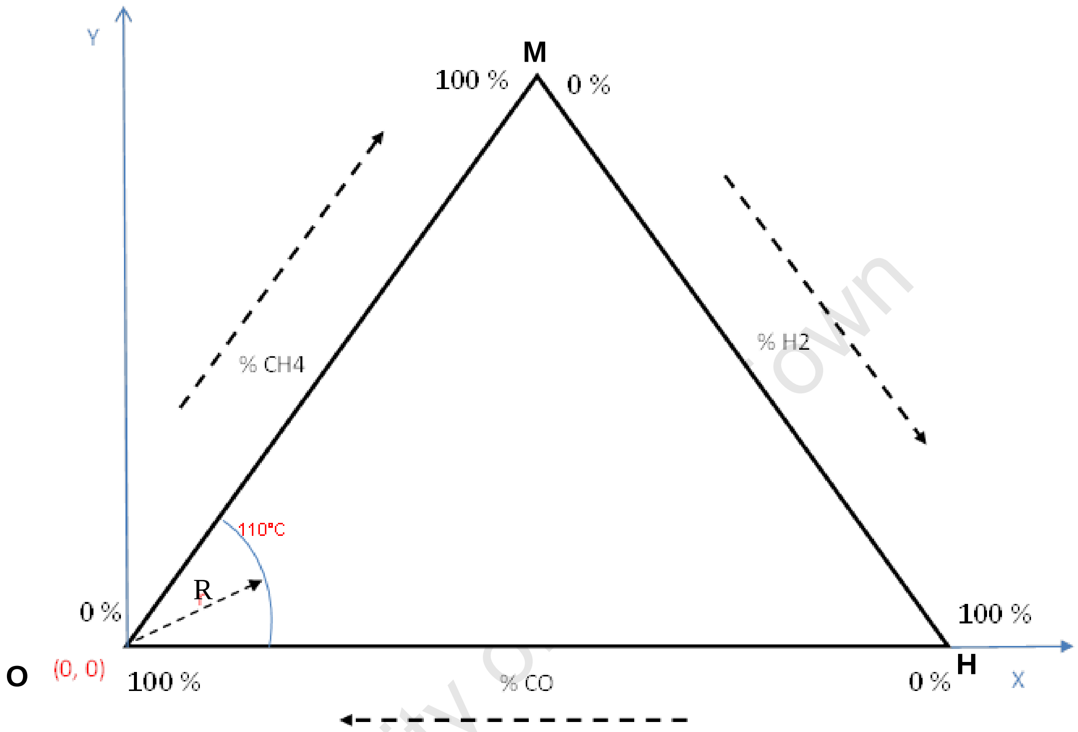


Figure 5-4: Boundary for Normal Temperature Limit

5.3.2. Defining (R) and Theta (θ)

R maybe defined as a vector representing the level of degradation of the insulation medium in the transformer. The degradation can be that of oil, paper or a combination of the two. The gradient and corresponding θ of R plays an important role in quantifying the amount of energy that may be present in a particular degradation level and at the same time satisfy the condition that increasing H2 is correlated to increasing levels of energy.

The maximum θ value is 60° with the highest gradient and should have the lowest impact due to the % H_2 being zero for the maximum θ (60°). The minimum θ value is 0° with the lowest gradient and should have the highest impact as % H_2 is 100%. Due to the LEDT modelling partial discharge as being within 98% to 100% of H_2, the lowest gradient is taken as θ being 1° as simulated on the LEDT for %H_2, %CH_4 and %CO being 98%, 2%, and 0% respectively.

The relationships as summarised in table 5.1 are tested:

For small θ values the energy levels are higher
For larger θ values the energy levels are lower
For shorter R-values the insulation degradation level is smaller
For longer R-values the insulation degradation level is larger

Table 5.1: Combinations of R-value and Theta (θ)

		θ	
		Small	Large
R	Short	Low degradation levels at a low energy level	Low degradation at high energy level
	Long	High degradation level at low energy level	High degradation level at high energy level

It is proposed that oil degradation produces predominantly methane (CH_4) and paper degradation produces predominantly carbon monoxide (CO).

From initial empirical evidence it was observed that initially the percentage of CO was high (> 80 %) due to normal degradation of paper at lower temperatures. This alone was not indicative of a fault or defective condition.
However, high levels of CO with corresponding significant levels of H_2 start to indicate a move towards a defective state. This also means significant involvement of paper insulation in the degradation process. This is observed in the levels of CO being within 30% to 80% of the sum of the three key gases.
For high levels of methane, there is significant involvement of oil in the defective condition. Thus for samples with dominant levels of methane the movement is along the methane axis. For low energy degradation, the polar points are within the 20% hydrogen level. As the energy increases, the movement is towards the centre of the triangle. For high levels of CH_4 with low levels of H_2 and CO this is representative of sparking in oil, which is discharges of low energy.

5.4. ADJUSTMENT OF NORMAL STATE LIMIT

By taking the impact of θ into consideration for the highest point temperature estimation it becomes clear that the R-value for indication of normal state will also have to be adjusted. The previous polar representation of r = 0.1732 was taken for normal state. By adjusting each R-value empirically the impact of the individual θ values figure 5-5 indicates the change of the normal state (dotted line) to the new adjusted normal state limit (solid line). These limits are further tested in the case studies and analysis of the full dissolved gas database.

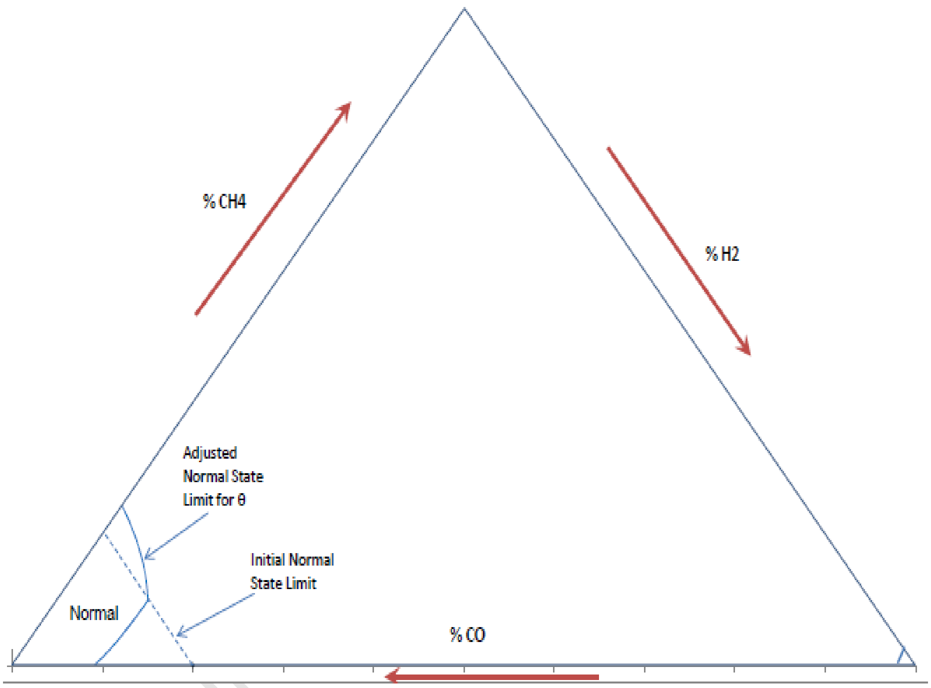


Figure 5-5: Adjustment of Normal State Limit

5.5. SUMMARY

The LEDT by nature provides a distribution of the amount of H_2, CH_4 and CO levels in the power transformer. These three gases also allow for some indication of the level of energy within the transformer. By making use of the polar plot concept the LEDT XY coordinates can be converted into a polar plot representation. This enables the R-value to represent a level of insulation degradation as represented by the three dissolved gases. The angle theta (θ) captures the impact of H_2, which is proportional to the amount of energy released within the transformer. The application of the θ value makes it necessary for the adjustment of the normal state to be in line with the energy dissipation for a particular degradation rate.

The following initial observations are made:

- From initial analysis of trends of transformer failures in locations containing paper insulation, it is suggested that for normal conditions, when the CO levels are higher than 80% the transformer appeared healthy.

- When the CO levels started to drop with increasing levels of hydrogen there was significant paper degradation.

- When the CH_4 levels started increasing there was significant oil degradation.

- High CO levels tend to dilute the effect of slightly elevated levels of hydrogen and methane.

CHAPTER 6

CASE STUDIES

6.1. INTRODUCTION

Chapter 4 and 5 provided a systematic development of a power transformer low energy degradation model which has taken the form of the Low Energy Degradation Triangle. It is envisaged that both degradation of cellulose and oil insulation will be effectively captured by the LEDT due to the presence of carbon monoxide and methane respectively.

Chapter 6 focuses on testing the LEDT on case studies of transformers that have either showed signs of or have already failed within Eskom's GSU transformer fleet. The 12 case studies form one of the key inputs into this research.

Further general analysis is performed on the remaining transformers to establish further trends and information in terms of positive triggers of defective state or of limitations that may exist in using the LEDT as a tool for detecting a change of transformer state from normal to defective.

A total of 201 GSU transformers was analysed with dissolved gas data ranging from 1987 to 2011. The transformer ratings range from 65 MVA to 760 MVA. The technology of plant included that of hydro, pumped storage, gas, OCGT and coal. 81% of the GSU transformers operate as base load units. Table 6.1 provides an overview of the number and technologies of the GSU transformers analysed in this study.

Table 6.1: Details of GSU Transformers Analysed

Rating (MVA)	Coal	Pumped Storage	Hydro	Gas		TOTAL
				Aero Derivative	OCGT	
65-100			4	6		**10**
101-350	43	10	4		14	**71**
350-650	28					**28**
651-1000	92					**92**
TOTAL	**163**	**10**	**8**	**6**	**14**	**201**

Table 6.2 provides the basic details of the GSU transformers that are used in the case studies.

Table 6.2: List of GSU Transformers in Case Studies

Case Study	Rating (MVA)	YOM	Year of Failure	Date of Failure	Age at Failure	Failure Mechanism
A	700	1988	2008	09-May-08	20	Elevated gas levels
B	700	1985	2004	14-Nov-04	19	Damage to interturn fault C phase HV winding
C	700	1987	2004	22-Dec-04	17	Insulation breakdown in HV winding
D	390	1970	2005	15-May-05	35	Interturn fault on the C phase HV winding.
E	390	1982	2004	30-May-04	22	interturn fault on B phase LV winding
F	700	1988	2004	16-May-04	16	Overheated Winding Leads
G	700	1988	2003	04-Jan-07	15	Interturn fault on HV winding
H	220	1985	2000	27-Jun-00	15	flashover of the red phase HV lead to the core clamp
I	220	1982	2005	14-May-05	23	Damage to B phase HV winding
J	700	1984	2005	30-Sep-05	21	Damage to B phase HV winding
K	700	1986	2005	27-Feb-05	19	Insulation breakdown between LV
L	100	1976	2001	28-Nov-01	25	Interturn fault on LV winding

6.2. CASE STUDIES

6.2.1. Case A: 700 MVA (22/420 kV, YOM: 1988) GSU Transformer Failure

Background:

After running under elevated gas levels the transformer was taken out of service for an on-site internal inspection on 9 May 2008. The internal inspection revealed discolouration on the top core clamp and blocking with burn marks on the A phase tapping leads [Chauke1].

LEDT:

Figure 6-1 is the Low Energy Degradation Triangle for this case study where the first trigger of defective state was received on 18 June 1996. On the LEDT due to the θ value this was within the adjusted boundary but the R-value was above the 0.173 limit. This trigger did not sustain the defective state where subsequent samples for the next four years were all in the normal state. The next defective state trigger was on the 7 November 2002 (due to the θ compensation) and then on the 13 November 2002. This was a true trigger as subsequent samples were in the defective region. The absolute ppm values for the three gases were H_2 1 ppm, CH_4 1ppm and CO 8 ppm. The sample on the 18 November 2003 indicated further deterioration with ppm values being; H_2 35 ppm, CH_4 15 ppm and CO 47 ppm. The progression of the trend was along the CO axis indicating an increasing percentage of H_2 with constant percentage of CH_4 and a decreasing percentage of CO. The distribution of the samples was more widespread in 2006 where the distribution started to contract in 2007 and further in 2008.

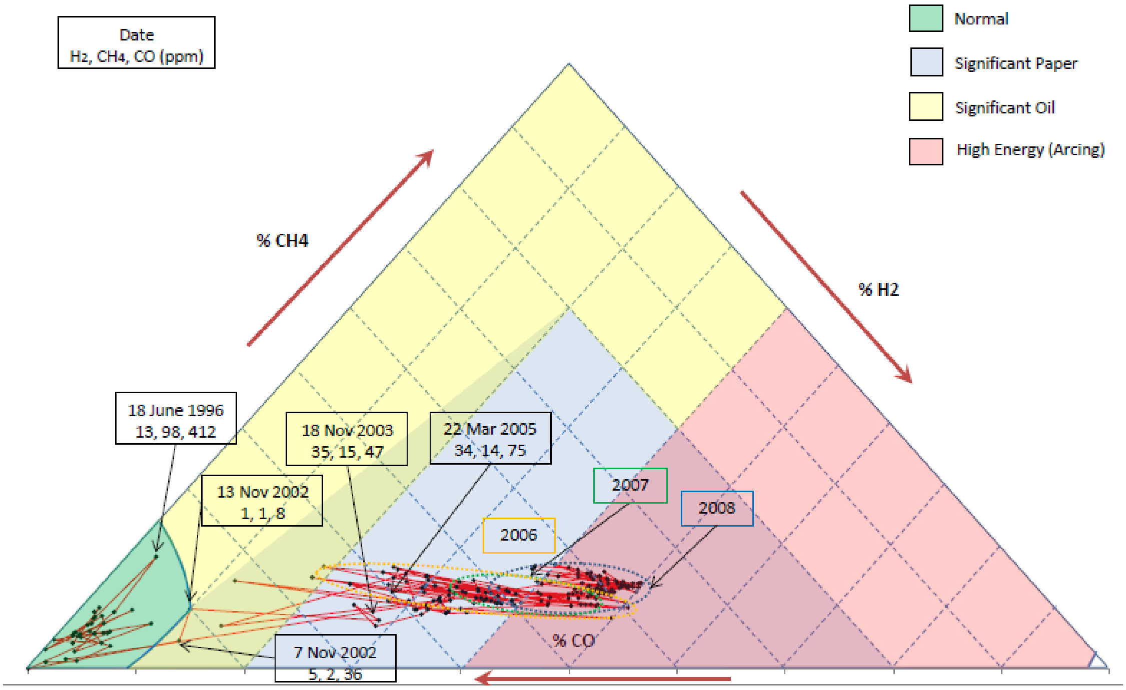


Figure 6-1: LEDT Case Study A

Combustible Gas Trend:

From figure 6-2 the combustible gas trend it is observed that initially the levels of carbon monoxide was high with elevated levels of methane. The transformer oil was then reconditioned after 22 October 2001. Evidence of this was seen in the next oil sample taken on 6 March 2002 where the gases all lowered in values. The most significant change was in carbon monoxide, methane and ethane. From the 13 November 2002 which was a trigger point in the LEDT the level of hydrogen started to increase with an up down trend until the 8 May 2005. During this period no conclusive diagnosis could be made just looking at the gas trends, however with the LEDT the trend was well into the defective region. On the 22 March 2005 the next step change in gas increase was noticed before the hydrogen levels started to take off above the 100 ppm levels. The methane levels continued at a level between 30-40 ppm until 17 April 2008 when the next change in gas levels occurred. This was the final change before failure occurred.

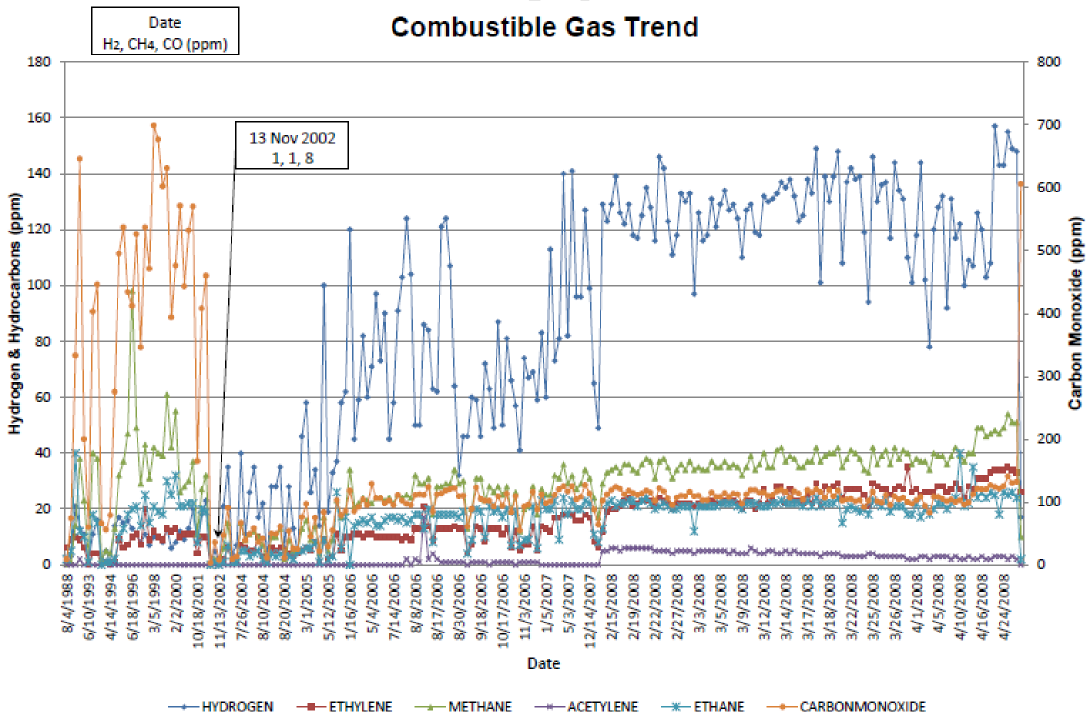


Figure 6-2: Combustible Gas Trend – Case Study A

R-Value

The R-value remained below the 0.173 limit from the period 1988 until the beginning of 1996. The first trigger out of this limit was 18 June 1996. This position however did not sustain until the next trigger on 7 November 2002 (due to compensation by θ on the LEDT) and 13 November 2003. From this point all R-values was out of the limit. This was a clear indication of a developing fault condition. The trigger on the 7 November 2002 was received at least 5 years and 4 months prior to being taken out of service.

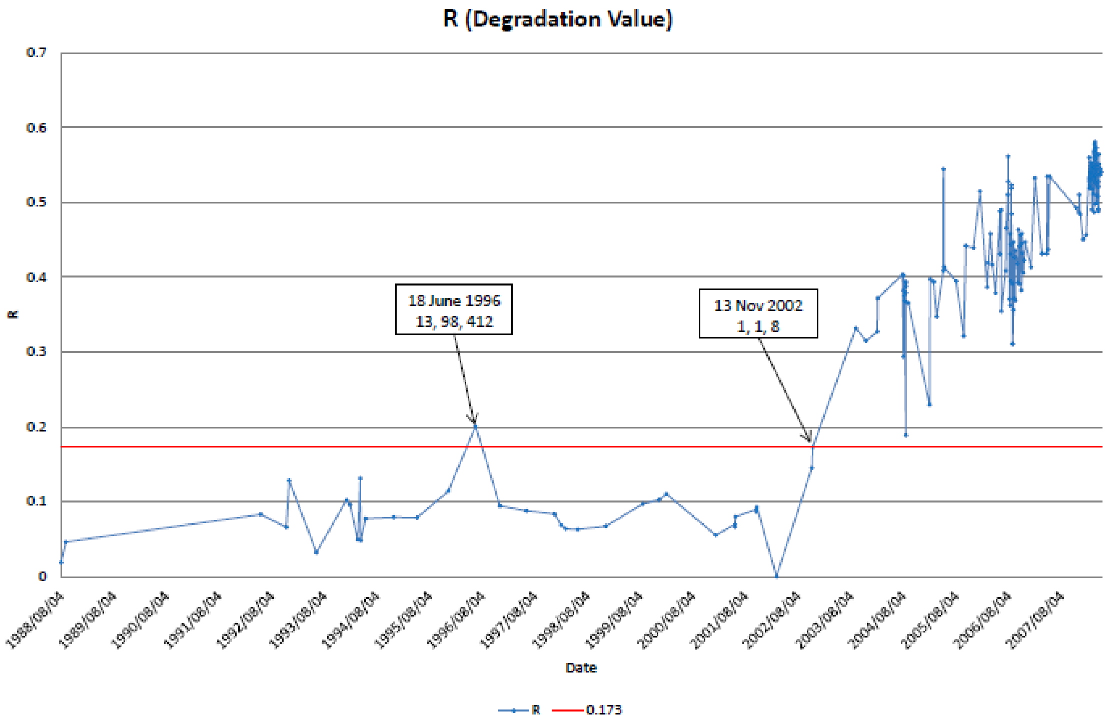


Figure 6-3: R-Value - Case Study A

Case Study A: Summary of Results

This case study A provides results indicating the early detection of a defective state. The trigger was received at least 5½ years before it was finally taken out of service. The initial result of normal state does correlate with the LEDT normal region where all results were within the normal boundary. When a defective trigger was received further results of the defective state was consistent with that of the LEDT. There was also an increasing trend of the R-value with time. Another positive aspect observed is that even though the combustible gas trends were erratically increasing and decreasing cyclically the LEDT was relatively insensitive to these changes such as to provide an increasing trend.

Case B: 700 MVA (20/300 kV, YOM: 1985) GSU Transformer Failure

Background [Ramos1]**:**

On the 14 November 2004 this 700MVA GSU transformer tripped on Buchholz protection due to increased gas level. The generator fault recorder data revealed no defects in the voltage and current signals prior to the trip and there was no Buchholz alarm prior to the transformer trip. The transformer operated satisfactorily for the past 18 years with just one major event on the 6 December 1995 where a three phase to earth fault was experienced on the HV yard due to portable three phase earths being left on the HV yard bus bar. The transformer oil was still original with a conservator air cell fitted in September 2000.
An age assessment study conducted on 8 September 2004 (3 months prior to failure) indicated evidence of oxidation with acidity of 0.08 mg KOH/g, low interfacial tension at 26 mN/m, with the oil colour darkening and furan results indicating a paper DP value between 300 and 320.

There was no evidence of oil expulsion but the accumulated gas was clearly visible inside the Buchholz Relay. The post mortem internal inspection revealed a conductor inter-turn short on the top HV C-phase winding between layers 14 to 42. The insulating paper on the copper conductors (strands) in the fault area below clack was damaged and in some cases indicated short circuits between strands with visual evidence of free copper particles and hammering on various clacks due to loose winding. Figures 6-4 and figure 6-5 provide visual evidence of the damaged areas as described above.

Figure 6-4: Inter turn Damage on HV Winding

Figure 6-5: Damage on Top HV C Phase

LEDT:

Figure 6-6 is the LEDT for case study B. The oil sample results in this case study from 1987 to 1996 was already in the defective state due to high levels of methane and hydrogen. In the LEDT the trend started to increase along the CH_4 axis indicating an increasing rate in the levels of methane with a consistent rate of production of hydrogen and carbon monoxide. The decrease in the percentage of CO from within 80% to eventually about 65% is an indication of paper involvement. This was also confirmed with the actual ppm values of CO still consistently being above 600 ppm.

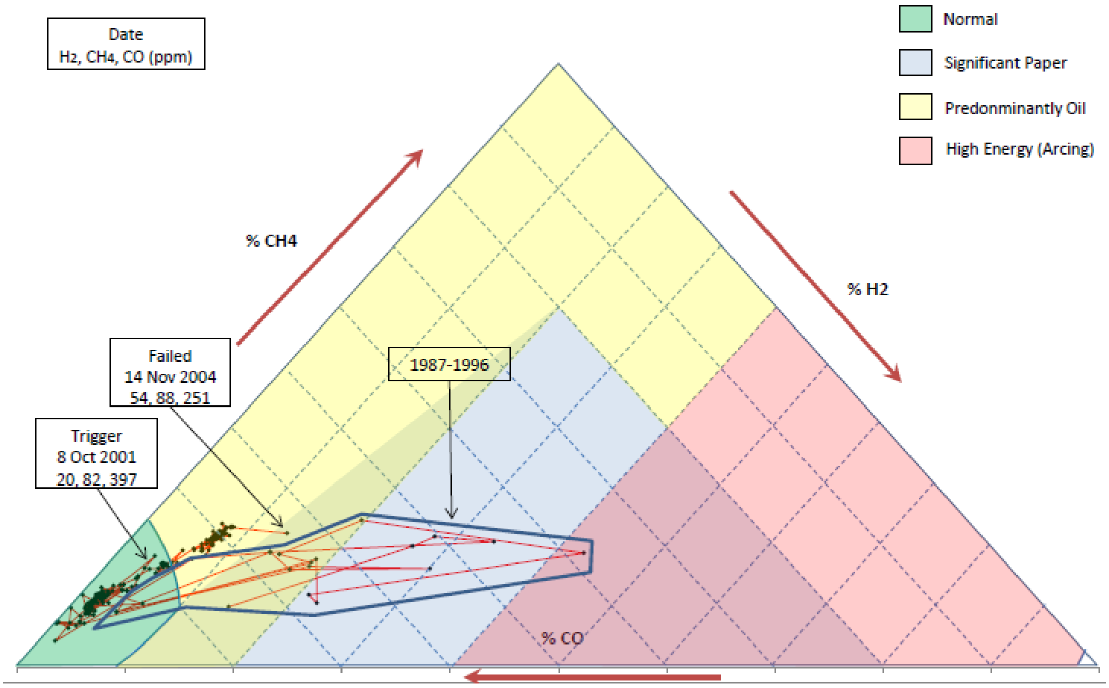


Figure 6-6: LEDT Case Study B

Combustible Gas Trend:

The combustible gas trend for case study B is presented in Figure 6-7. The first oil sample recorded was on 30 October 1987. This sample was already in the defective region indicating an early fault condition. Subsequent oil samples indicated a deteriorating condition. There were some elevated levels of hydrogen and methane. The transformer oil was then reconditioned before the sample on 10 August 1989 where all the dissolved gases decreased to within the normal region thereafter. However from the combustible gas trend it is seen that the carbon monoxide and hydrogen levels started to immediately increase.

On the 6 December 1995 two faults occurred in the HV Yard, relatively close to this transformer when portable three phase earths were left on the HV Yard bus bar. This event caused a step increase in combustible gas levels in the oil. The hydrogen levels however did not have an increasing trend. The load of the transformer was adjusted to enable the unit to be in operation. The production of dissolved gases correlated to the increase and decrease in the loading. This kept the samples within the normal region. It was only when the first trigger was received on the R-value on the 8 October 2001 that the hydrogen levels started to increase. The CO levels were high in the region of 750 to 1000 ppm indicating severe paper degradation.

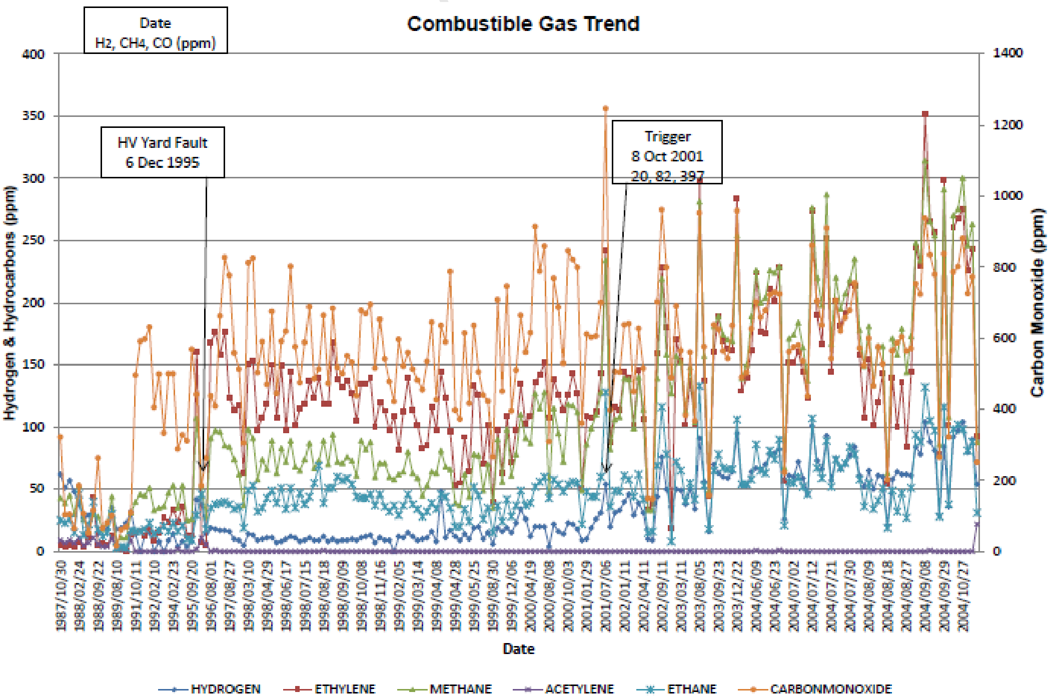


Figure 6-7: Combustible Gas Trend - Case Study B

R-Value

As with the combustible gas trend and LEDT the initial R-values in figure 6-8 was also above the limit. After the oil reconditioning the R-values went below the limit of 0.173. It is observed that after the trigger on the 8 October 2001 the R-values displayed an increasing trend above the limit value. This was indicative of the development of an imminent fault condition.

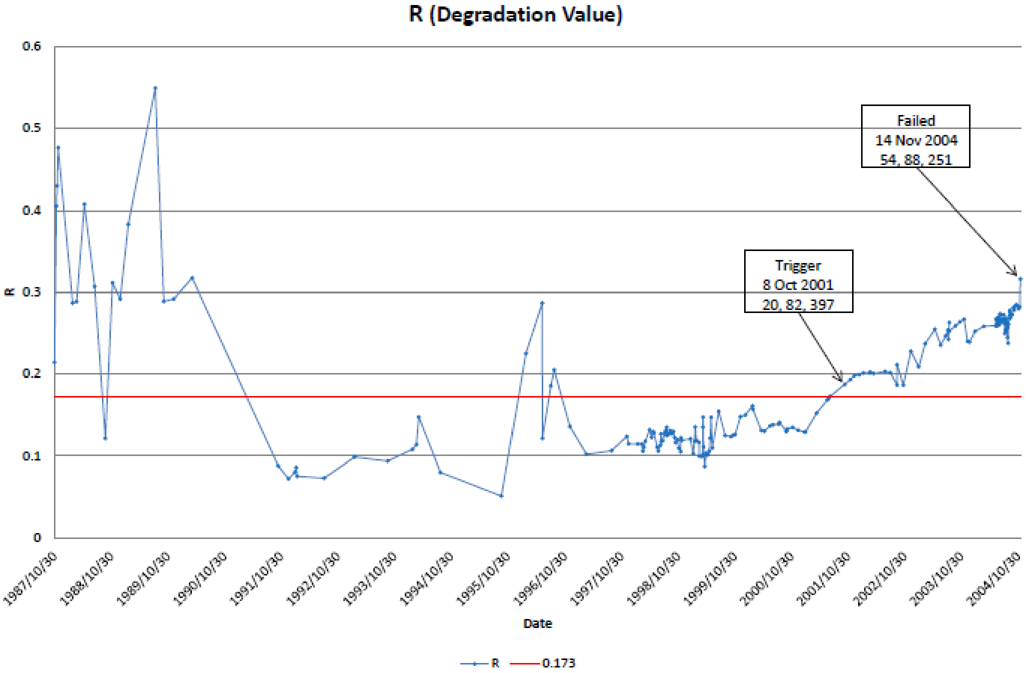


Figure 6-8: R-Value - Case Study B

Case Study B: Summary of Results

In this case study B it is found that the initial oil results recorded were already in the defective region of the LEDT. After oil reconditioning the samples went down but with the HV yard incident there was a step change in the gases produced. The LEDT was consistent with capturing these changes with the trends within. The trigger received on the 8 October 2001 was at least 3 years before the failure occurred which took the transformer out of service. The oil sample results when normal and out of normal did correlate well with the LEDT normal and defective regions. There was also an increasing trend of the R-value with time after the defective trigger was received. Once again even though the combustible gas trends were erratically increasing and decreasing the LEDT and R-value was relatively insensitive to these changes such as to provide an increasing trend.

6.2.2. Case C: 700 MVA (20/300 kV, YOM: 1987) GSU Transformer Failure

Background [Ramos2]:

On 22 December 2004 this 700 MVA GSU transformer tripped from 593 MW on Buchholz and electrical protection. This transformer was initially commissioned in another unit since 1988 and was then used to replace a failed GSU transformer on 29 November 2004 due to its unit being on a long general outage to allow for at least one unit being returned to service.

The original oil was changed with regenerated oil. This GSU transformer only lasted 23 days in its new position before failure.

The post mortem revealed damage to HV C-phase winding in the form of inter-strand and inter-turn short circuits. Figure 6-9 and figure 6-10 captures some of the damage experienced on the HV C phase windings and LV exit leads.

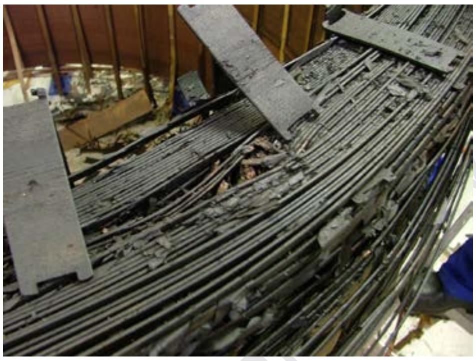


Figure 6-9: Inter-turn short circuits

Figure 6-10: Thermal Heating LV Exit Leads

LEDT:

Figure 6-11 provides the LEDT representation leading up to this incident. It was observed that the transformer moved to an out of normal state on 7 February 2000 where the condition remained in this area until it was relocated to the other unit. This was a clear indication that even though the conventional DGA did not indicate any major concerns the Low Energy Degradation Triangle identified a budding fault condition. The oil change out as evident in the oil sample taken on the 20 December 2004 also masked the defective state due to the sample point now being within the normal region of the LEDT.

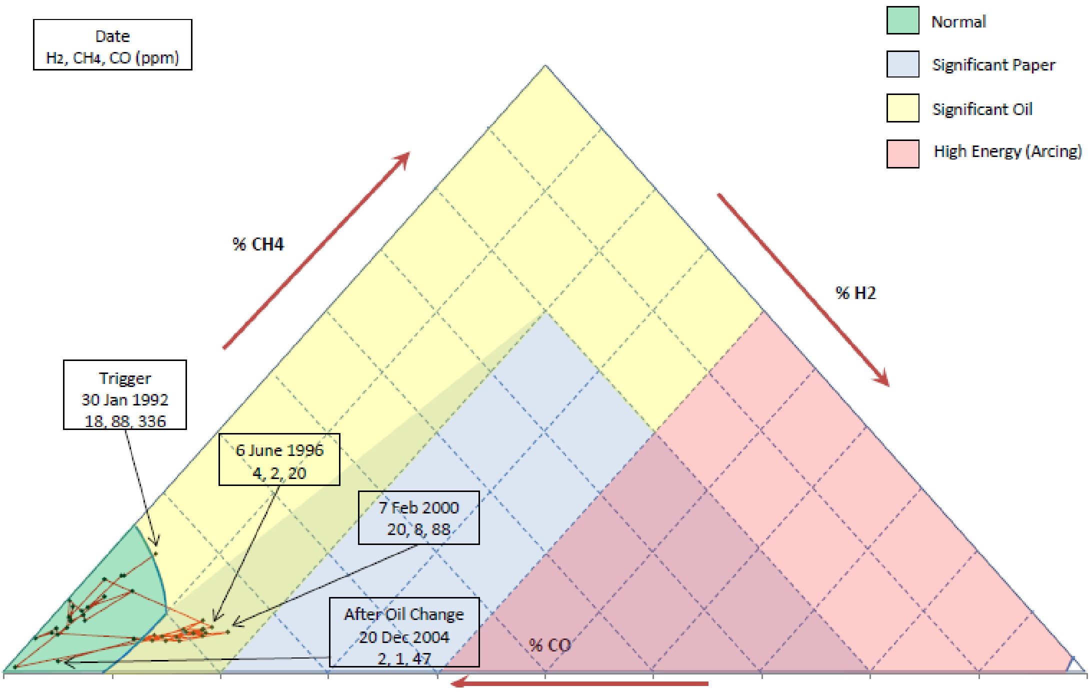


Figure 6-11: LEDT Case Study C

Combustible Gas Trend:

From the combustible gas trend in figure 6-12 it is observed that the first oil sample on record was on 30 January 1992 which was already in the defective region with H_2, CH_4 and CO being 18 ppm, 88 ppm, and 336 ppm respectively. Subsequent results over the next year were within the normal region. The methane levels were initially high but then started to be moderate around 20 ppm. The hydrogen levels started to increase but were still within 60 ppm. It is also interesting that the carbon monoxide levels were low. The last sample recorded in this case study on the 20 December 2004 indicated a drastic decrease in the combustible gases due to the oil change out.

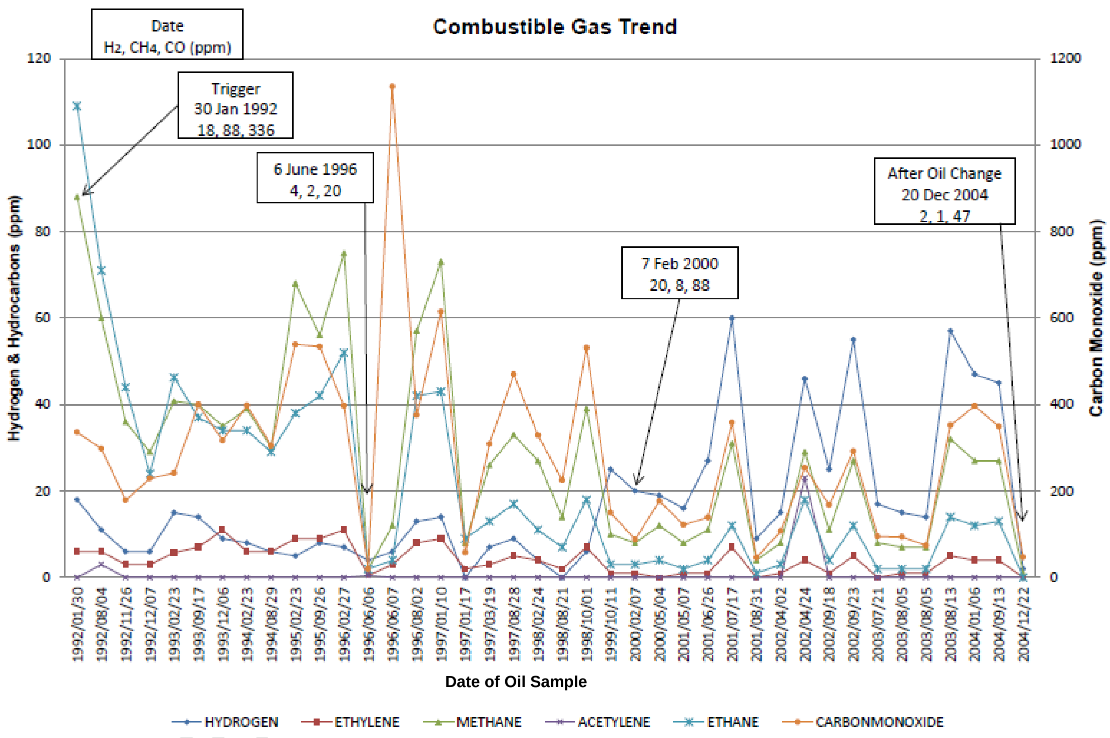


Figure 6-12: Combustible Gas Trend - Case C

R-Value

The R-value plot on figure 6-13 identifies the initial defective state of the transformer on the 30 January 1992. The second trigger was received on 6 June 1996 and the third trigger was on the 7 February 2000. After the third trigger was received the R-values recorded were consistently above the normal limit indicating a defective condition. The reinstallation sample in December 2004 represented the oil change out with the R-value being within the 0.173 limit.

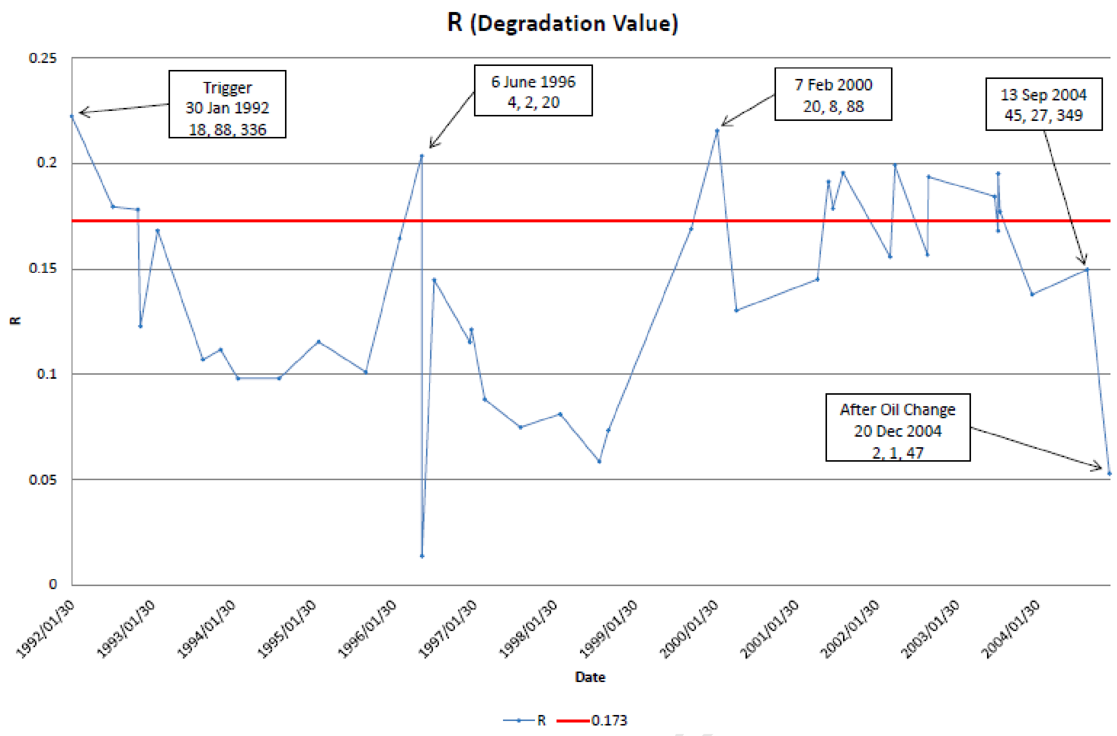


Figure 6-13: R-Value - Case Study C

Case Study C: Summary of Results

The post mortem design review revealed inadequate cooling on the top and exit leads of the winding. The acidity level increased from 0.06 to 0.11 mg KOH/g within the year which was supported by the high levels of sludge on the windings. The interfacial tension also decreased over this period. The LEDT was able to detect the defective state of the transformer with the last significant trigger received at least four and a half years before the failure occurred. In this case study it was found that θ did have an influence on the level of energy that was present. Although the latter R-values were below the 0.173 limit, due to the effect of θ, on the LEDT they were in the defective region. This emphasises the importance of using the θ compensation on the LEDT plot. It was also noted that the oil change out, only had the effect of masking the dissolved gas values as the imminent defective state was still present within the transformer.

6.2.3. Case D: 390 MVA (11/275 kV, YOM: 1970) GSU Transformer Failure

Background [Bizior1]:

On the 15 May 2005 this 390 MVA GSU transformer failed. During the previous unit outage the transformer oil was purified to remove moisture.

The transformer was initially commissioned in October 1971. In 1996 the transformer was involved in a coupling transformer incident with another unit and was sent to the Eskom workshop for repair on April 1997. It was reinstalled in February 2000 where it started to gas and was removed for an internal inspection which revealed loose flexible connections. This was repaired on-site and returned to service.

The gassing continued slowly and the transformer was removed from service for an internal inspection at the Eskom transformer workshop which revealed a fault on the HV winding crossover. This was repaired. The impulse test although acceptable revealed the absolute value of the C-phase (300 pico-coulombs) PD test results being higher than that for the A and B phases (200 pico coulombs).

The transformer was then installed on 14 June 2004. Between September-December 2004 the on-line DGA indicated an upward trend. The unit was then shut down for the generator replacement project and the last sample was taken on 22 December 2004. The transformer was returned to service on 25 March 2005 before undergoing oil purification where it failed on 15 May 2005. After the failure the internal inspection revealed damage to the C-phase HV winding as depicted in figure 6-14.

Figure 6-14: Case Study D - Damage on C phase HV winding

LEDT:

Figure 6-15 is the LEDT of Case Study D for the period 1991 to 1997. During this period the oil samples remained in the normal region until the first trigger on the 11 September 1996 with hydrogen being 59 ppm, methane 197 ppm and carbon monoxide 322 ppm. This was a sample taken after this transformer was involved in an incident with a coupling transformer. Samples thereafter were all in the defective region and the trend was along the $\%CH_4$ axis. The transformer was then taken out of service in March 1997 for repairs.

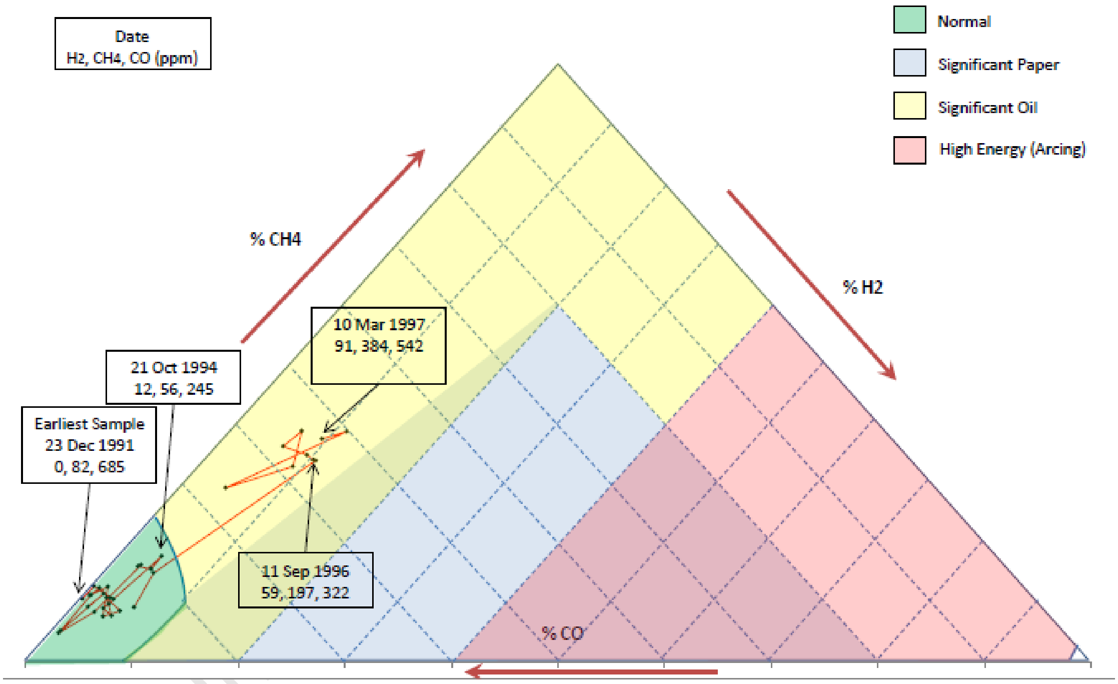


Figure 6-15: LEDT Case Study D 1991-1997

The LEDT in figure 6-16 is for case study D for the period from 2000 to 2005. The trend recorded at the top of the triangle was in the second period after the transformer was repaired. This was from 4 January 2000 to 13 March 2000. As can be seen from this LEDT the transformer was already in a really bad state. The recorded sample values at commissioning were 225 ppm hydrogen, 434 ppm methane and 112 ppm carbon monoxide. On-site internal inspection revealed loose flexible connections, which were repaired on-site and returned to service. The trend still progressed towards the upper region of the triangle and finally the transformer was taken out of service on 13 March 2000 where the recorded values for hydrogen, methane and carbon monoxide were 166 ppm, 530 ppm and 27 ppm respectively. The transformer was sent to the Eskom transformer repair shop for repairs.

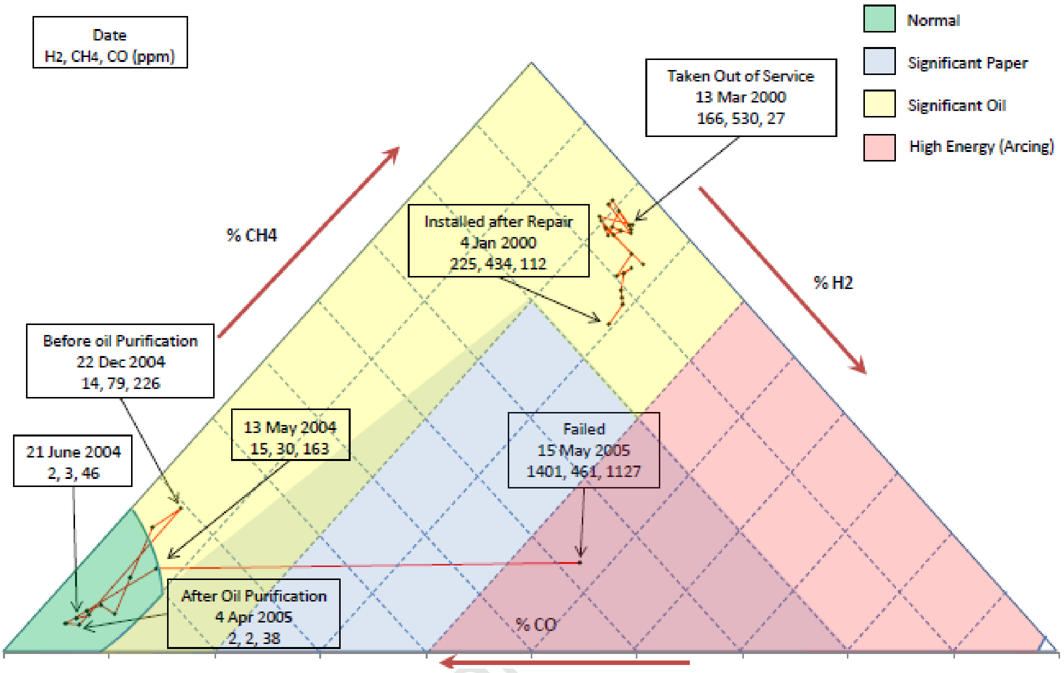


Figure 6-16: LEDT Case Study D 2000-2005

The transformer was then installed on the 14 June 2004. The oil sample results were in the normal region but soon after as observed in figure 6-16 the trend started to move into the defective region. The oil was then purified in an outage in December 2004 where the sample taken before this on the 22 December 2004 revealed hydrogen, methane and carbon monoxide to be 14 ppm, 79 ppm and 226 ppm respectively. After the oil purification these values were 2 ppm, 2 ppm and 38 ppm accordingly moving the transformer state back into the normal region. The next trigger was received with the oil sample taken on the 13 May 2004, a day before the failure.

Combustible Gas Trend

The combustible gas trends as indicated in figure 6-17 starts off with high levels of carbon monoxide and relatively moderate levels of methane. The methane levels started to increase after the coupling transformer incident in 1996. The trends thereafter decreased due to the transformer been taken out of service for repairs but then started to increase again after installation on 4 January 2000. Even after the repair and reconditioning of the oil, the methane levels continued to increase at a severe rate until it was taken out of service for repairs. The effects of oil purification were also evident in the trend for December 2004 before the failure in May 2005.

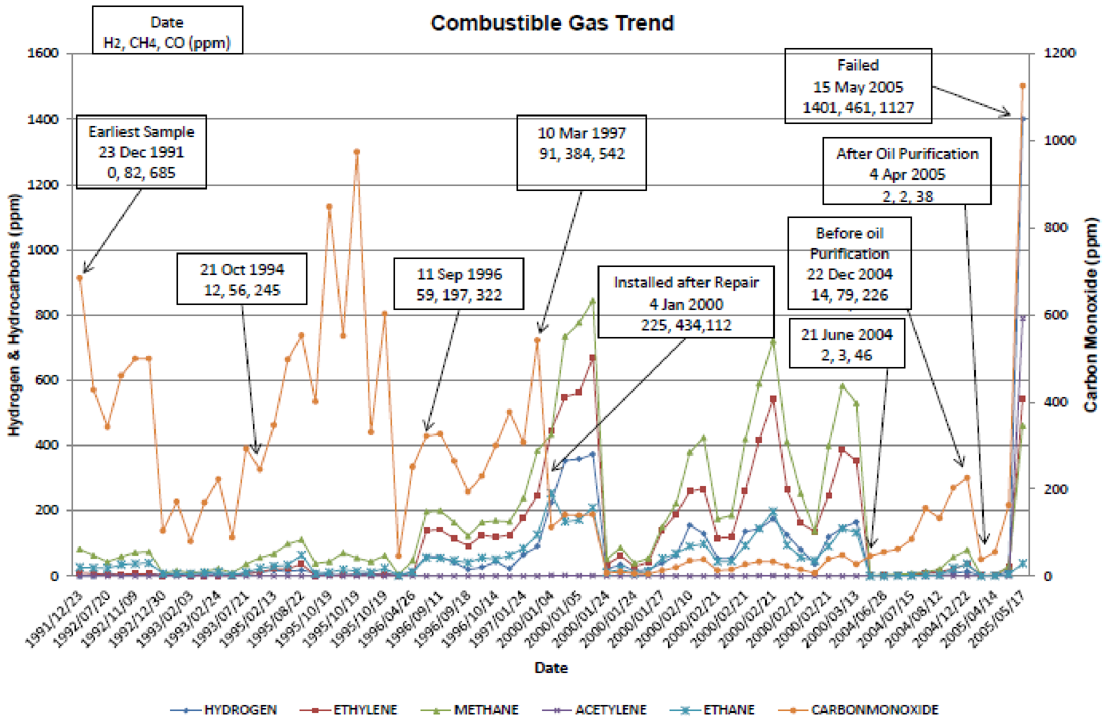


Figure 6-17: Combustible Gas Trend - Case Study D

R-Value

Figure 6-18 indicates the plot for the R-value which for the initial samples was below the 0.173 limit with the first trigger out of this limit was 21 October 1994. The next trigger was on the on 11 September 1996 after the coupling transformer incident. The R-values thereafter remained in the defective region, even after the transformer was reinstalled in January 2000 after the on-site repair. When the transformer was sent to the Eskom repair shop in 2004 the samples started in the normal region but soon immediately moved into the defective region. This was once again noted after the purification of the oil where it moved into the defective region almost immediately thereafter.

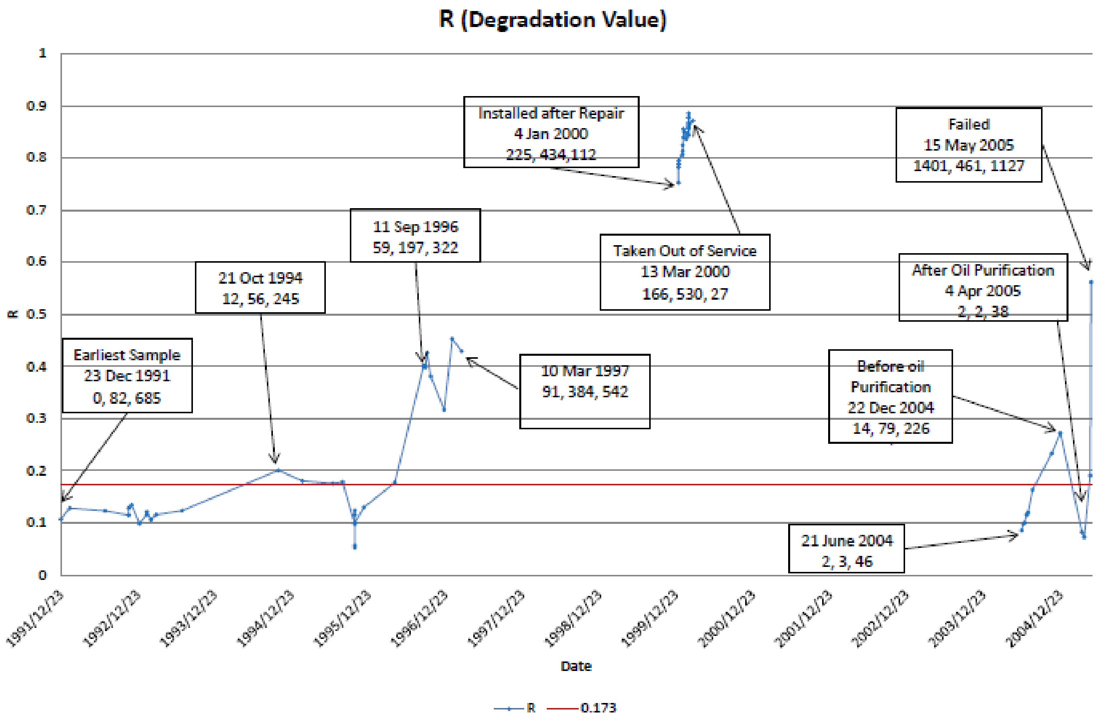


Figure 6-18: R-Value - Case Study D

Case Study D: Summary of Results

In this case study D the initial oil results recorded were in the normal region of the LEDT. Shortly after the coupling transformer incident the samples moved into the defective region. The LEDT once again was consistent with capturing these changes. The oil sample results correlated with the LEDT normal and defective regions.

An interesting observation is made in the period when the transformer was installed in early 2000 where the oil sample results were focused on the top of the triangle. These were for high levels of methane and moderate levels of carbon monoxide. However after the on-site repair and with the reconditioning of the oil the actual ppm values of the gases decreased but the oil samples still remained in the top region of the triangle indicating that the ratio of these gases was still the same but in lower ppm values. This interesting observation provides some indication that the LEDT maybe insensitive to fluctuations in the actual ppm values.

6.2.4. Case E: 390 MVA (15/275 kV, YOM: 1982) GSU Transformer Failure

Background [McGhee1]:

On the 30 May 2004 this 390 MVA GSU transformer failed. There was no external damage to the transformer however the on-site electrical tests confirmed that the low voltage windings were down to earth. This transformer was the spare transformer, which was used between units for only approximately 146 months prior to the fault.

The evidence of the inter turn fault was difficult to find due to the extent of the damage on the B-phase LV winding but observations on the other two windings revealed that:

- There was direct contact between the strips and conductors due to the spacers between disks being too short
- There were numerous burrs found on the conductors
- The insulation cylinder was missing between the HV and LV winding
- There were no additional strips at the transposition to prevent scissoring

The first period as highlighted in figure 6-19, green dotted circle was from 1 January 1991 to 5 April 1996. The second period was from 1 February 1997 to 5 October 1999 as indicated by the orange dotted region in figure 6-19. The third period was from 6 March 2000 up to the failure on 30 May 2004 as indicated in figure 6-20.

LEDT:

From Figure 6-19 the earliest sample recorded was on the 12 October 1991, which was already in the defective region with H_2, CH_4 and CO ppm values being 0 ppm, 18 ppm and 39 ppm respectively. The transformer operated in this region along the %CH_4 axis.

The first sample recorded for the second period was from 2 December 1997. This sample was just outside the defective region boundary as indicated in figure 6-19. Subsequent samples were just within the normal region. The transformer was then taken out of service on 15 September 1999 due to poor oil quality.

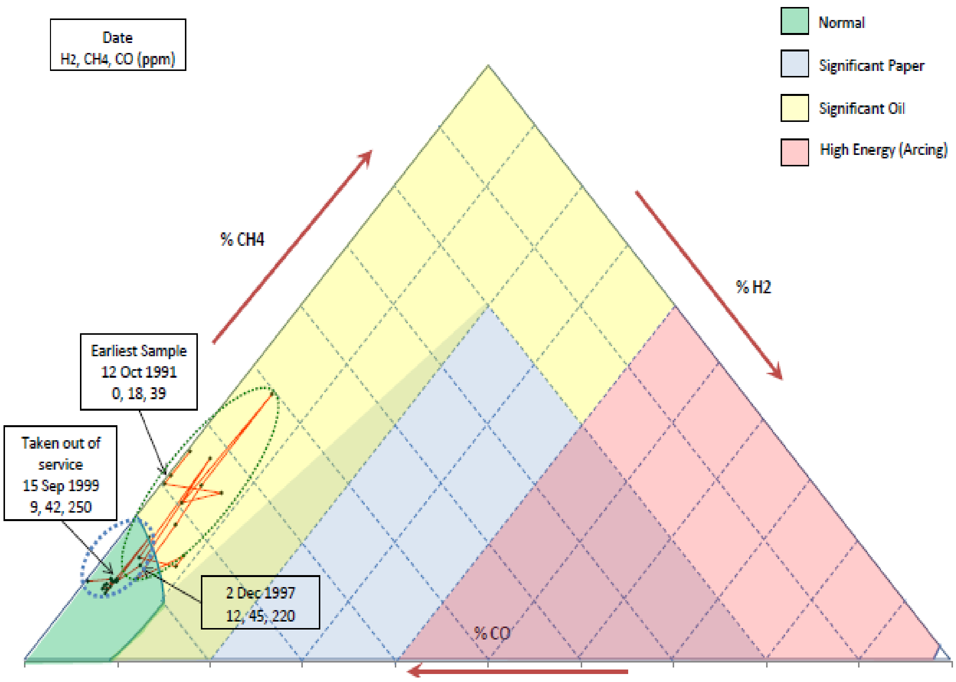


Figure 6-19: LEDT-1 Case Study E

The transformer was then sent to the Eskom repair workshop for dry out. The third period was from 6 March 2000 up to the failure on 30 May 2004 as indicated in figure 6-20. The sample on the 6 March 2000 was within the normal region. The first trigger was received on 5 September 2000 where subsequent samples remained in this region until the 24 April 2003 where there was a significant movement towards the centre of the triangle. There was further movement towards the centre where the samples remain in this area for about nine months before failure on 30 May 2004.

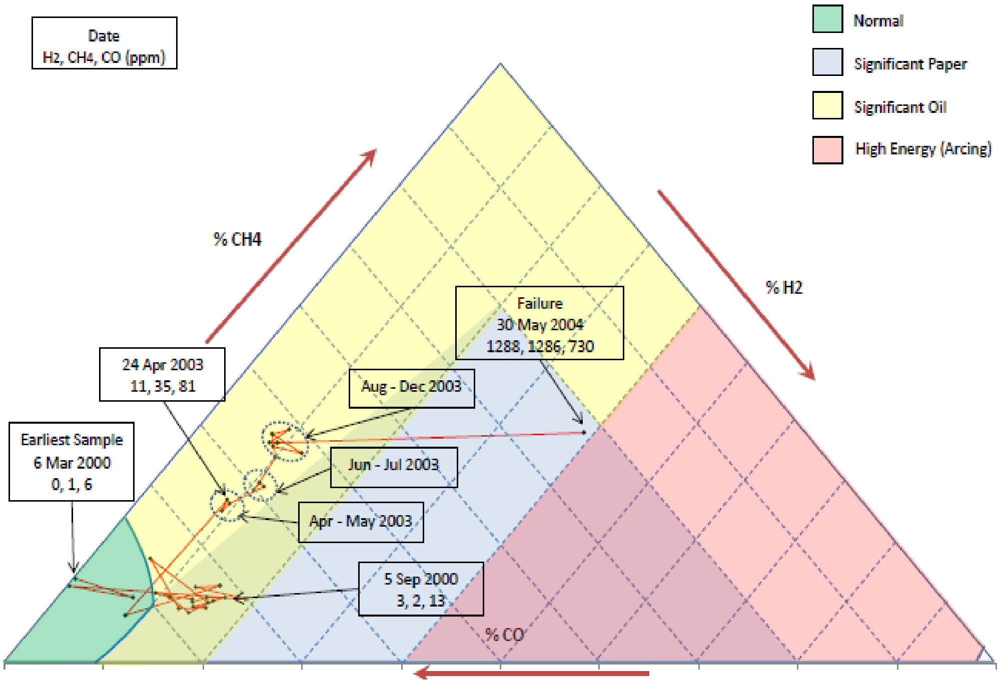


Figure 6-20: LEDT-2 Case Study E

Combustible Gas Trend:

The combustible gas trend in figure 6-21 starts off with high levels of ethane and methane with relatively low levels of carbon monoxide and hydrogen. This trend maintained until the beginning of 1997 when the levels of carbon monoxide started to increase beyond ethane and methane although the latter two gases continued to maintain moderate levels of production. The repair period was clear from samples starting on 6 march 2000 where all dissolved gas values were low and within the normal region of the LEDT. Due to the low levels of carbon monoxide a defective state trigger was received on 5 September 2000. This defective state maintained until the next major trigger on 24 April 2003 where the methane levels started to increase and be the dominant gas with further increases in ethane and hydrogen. The rate of increase maintained until failure on 30 May 2004.

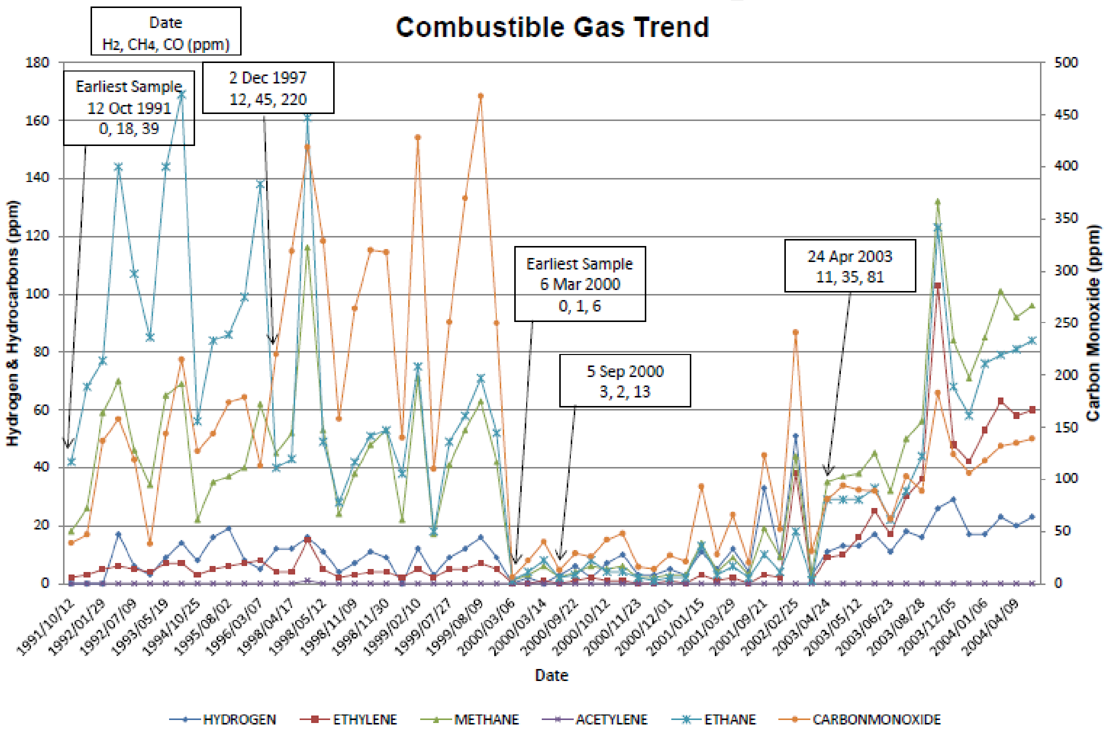


Figure 6-21: Combustible Gas Trend - Case Study E

R-Value:

The R-value correlated well with the initial defective dissolved gas results and remained in the defective region of the triangle until the transformer was repaired and returned to service. The first defective state trigger after this installation was received on 5 September 2000 as evident in figure 6-22. The R-values then continued in the defective region except for the sample on the 6 November 2002. The R-values then started an increasing trend until failure on 30 May 2004. It is once again noted that the R-values correlated well to the defective dissolved gases picked up from the oil samples.

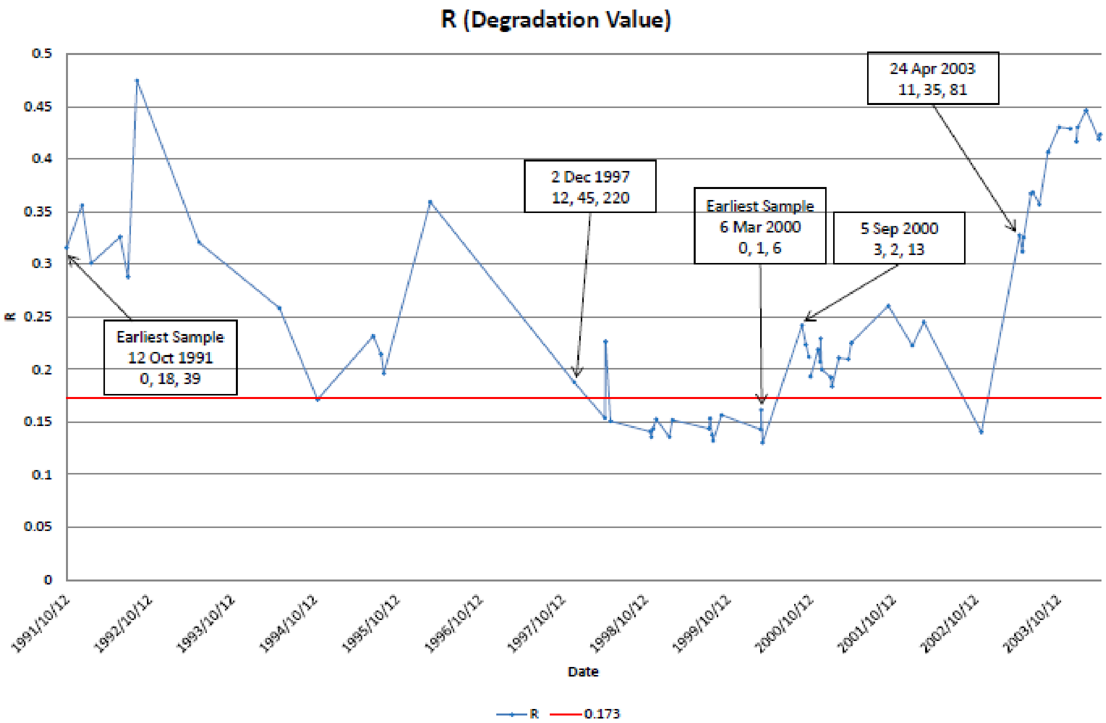


Figure 6-22: R-Value - Case Study E

Case Study E: Summary of Results

In this case study E the initial oil results recorded were in the defective region of the LEDT. The LEDT normal and defective regions correlated well with the oil sample results. The trigger received on the 24 April 2003 was at least one year before the failure occurred which took the transformer out of service. There was also an increasing trend of the R-value with time after the defective trigger was received.

6.2.5. Case F: 700 MVA (22/420 kV, YOM: 1988) GSU Transformer Failure

Background:

The following case study involves a 700 MVA GSU transformer that indicated increasing gassing trends before shut down in 2004 for an internal inspection. Prior to this incident the transformer was located with a different generating unit and was taken off line due to an increase in acetylene levels from June 2002. The core and core clamps megger tested down to earth with the visual inspection revealing insulation damaged between the core and core clamp feet.

The transformer was repaired and was commissioned in the new location (unit) on 23 May 2003. Shortly thereafter, the dissolved gas analysis of oil samples taken on 27 June 2003 indicated sharp movement towards elevated degradation energy levels as depicted on the Low-Energy Triangle plotted in figure 6-24. Subsequent oil samples indicated a worsening state for the transformer.

On 16 May 2004 the transformer was taken off line for an internal inspection. During the internal inspection it was found that the blue phase HV exit lead conductors had burnt away. Upon further inspection it was also found that the LV winding exit leads showed signs of severe overheating. See pictures in figure 6-23 for the extent of the damage.

Figure 6-23: Evidence of Failure

LEDT:

From the LEDT in figure 6-24 it can be seen that the oil samples for the year 2000 and 2001 were within the normal region. The first trigger was received on 26 July 2002 where subsequent samples were focused on this region. With the onset of acetylene levels the transformer was taken out and then repaired.

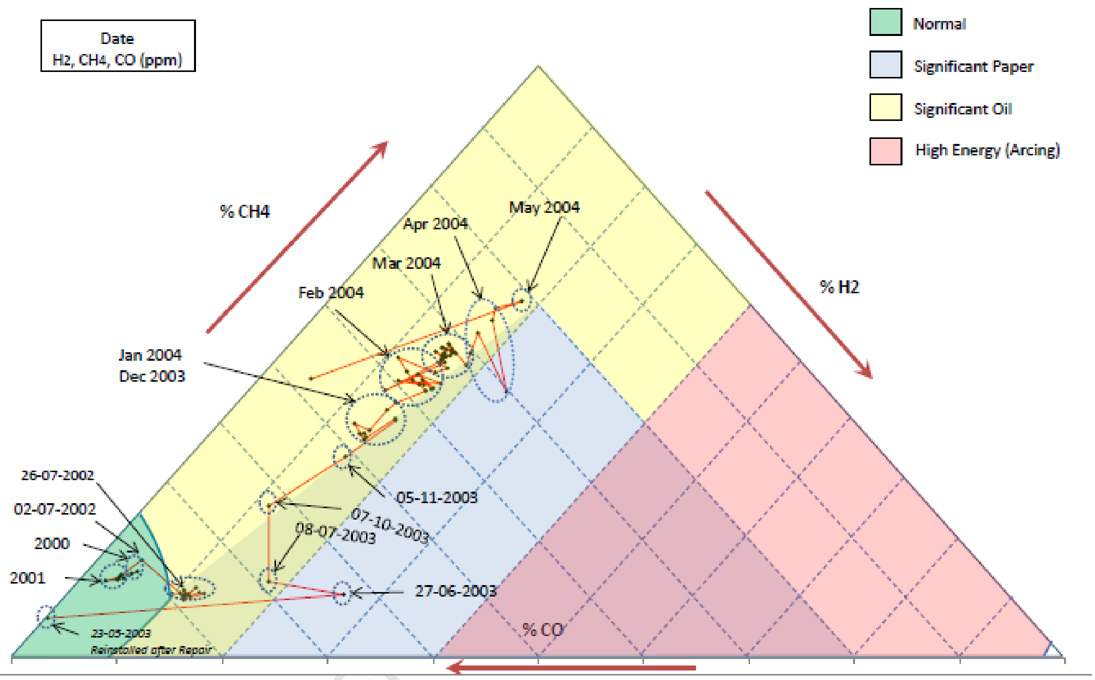


Figure 6-24: LEDT Case Study F

After the repair, the reinstallation oil sample taken on the 23 May 2003 was within the normal region. Although apparently repaired after the 2002 incident, the LEDT once again indicated, within a few weeks of being returned to service on the 27 June 2003, that the transformer was again in a defective state. Samples taken on the 8 July 2003, 7 October 2003 and 5 November 2003 indicated a progressing defective state. Between December 2003 and May 2004 the LEDT indicated a steady increase in the level of degradation. The slightly erratic path to failure is probably related to the variability of the analysis of the dissolved gases under changing conditions of ambient temperature and transformer loading.

Combustible Gas Trend:

Figure 6-25 represents the combustible gas trend in this case study. It was observed that initially the levels of carbon monoxide were high with elevated levels of methane and ethylene with some acetylene. The transformer was then taken out of service. This was evident in the decrease in the levels of gases with the reinstallation sample on the 23 May 2003. It was then evident that the gases started to immediately increase, especially that of methane and ethylene. On the 30 March 2003 the loading of the transformer was decreased. The subsequent oil samples however continued to increase in value until the transformer was removed from service on 4 May 2004.

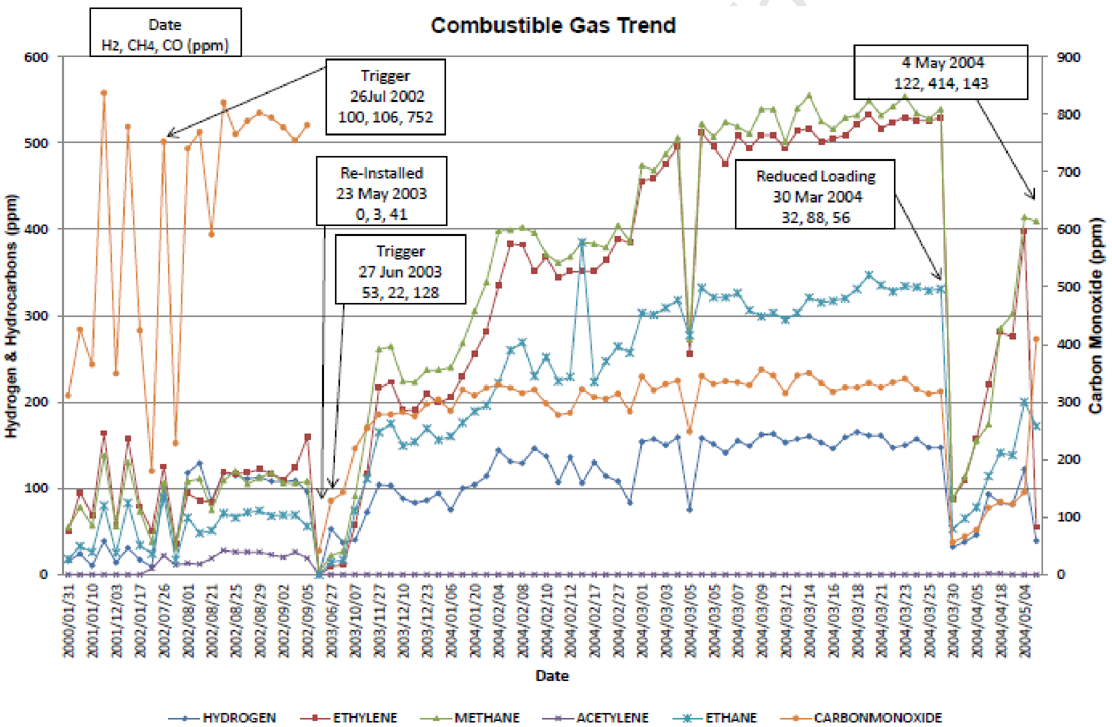


Figure 6-25: Combustible Gas Trend – Case Study F

R-Value

Figure 6-26 is the R-value representation in this case study. The R-value remained below the 0.173 limit until the first trigger on 26 July 2002. The transformer was then taken out of service in 2002 and reinstalled again on 23 May 2003 which shows the position in R-Value plot being within the 0.173 limit. The next trigger received on the 27 June 2003 was the beginning of the defective state of the transformer in this period.

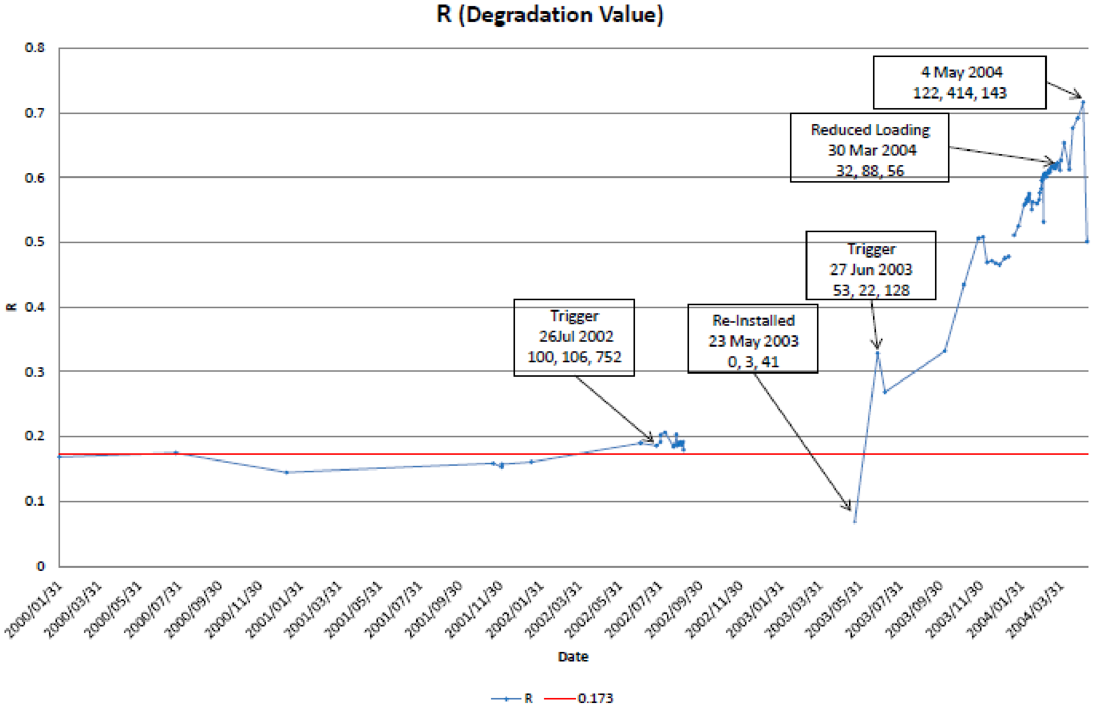


Figure 6-26: R-Value - Case Study F

Case Study F: Summary of Results

This case study F provides results indicating the imminent development of a fault condition in a 700 MVA GSU transformer. The first trigger after the transformer was reinstalled after repairs on 23 May 2003 was received at least one year before it was finally taken out of service. The initial result of normal state does correlate with the LEDT normal region where all results were within the normal boundary. When a defective trigger was received the subsequent results of defective state was consistent with that of the LEDT. There was also an increasing trend of the R-value with time. It is observed that even though there was a decrease in the levels of gases from 30 March 2004 as observed in the combustible gas trends in figure 6-25, the R-value trend still maintained the upward trend without major decreases.

6.2.6. Case G: 700 MVA (22/420 kV, YOM: 1988) GSU Transformer Failure

Background:

This 700 MVA GSU transformer first failed in late 2003. It was then sent to the Eskom repair shop for a total rewind and then installed on the 28 May 2004. This GSU transformer then failed on the 4 January 2007.

LEDT:

Figure 6-27 provides the LEDT representation for this case study. It is observed that after repair and replacement of oil the first oil sample on the 28 May 2004 was in the normal region.

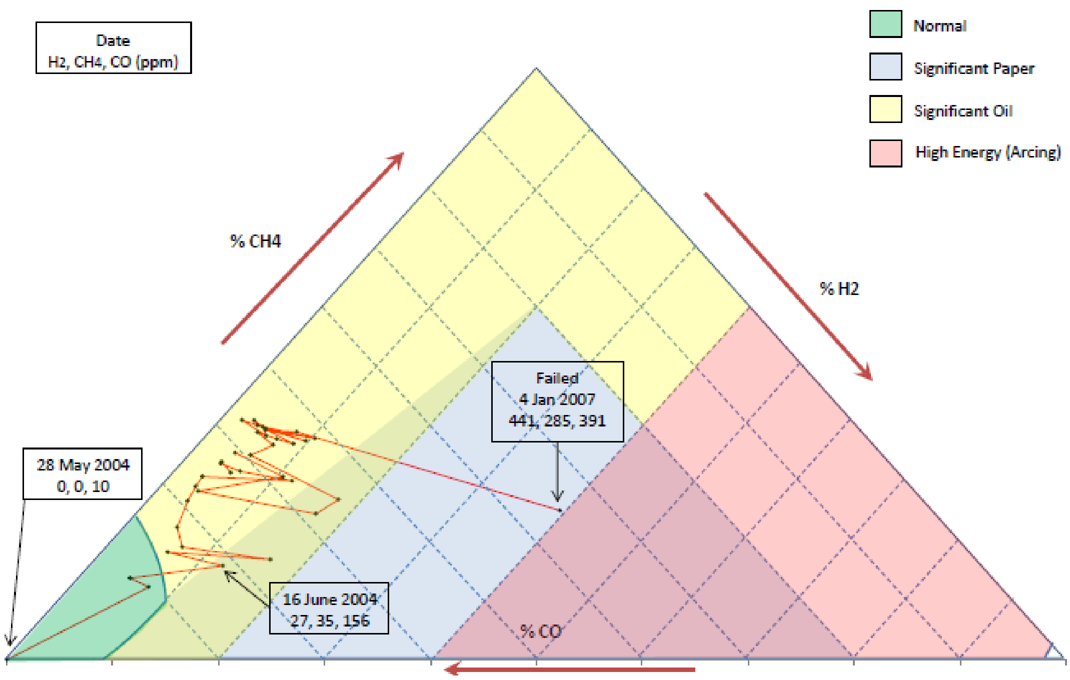


Figure 6-27: LEDT Case Study G

The next few oil samples started to immediately move into the defective state and by the 16 June 2004 the transformer was in the defective state. All subsequent samples were in the defective region and there was upward movement indicating a significant increase in the level of methane.

Combustible Gas Trend:

The combustible gas trend in figure 6-28 indicates a steady increase in the levels of ethane and methane from the time the transformer was commissioned into service. It is interesting to note that the ethane levels throughout the period have increased significantly with low levels of hydrogen and ethylene. The levels of methane were above 100 ppm for the majority of this period. Both ethylene and acetylene were at low levels indicating that the fault temperature was not greater than 600 °C.

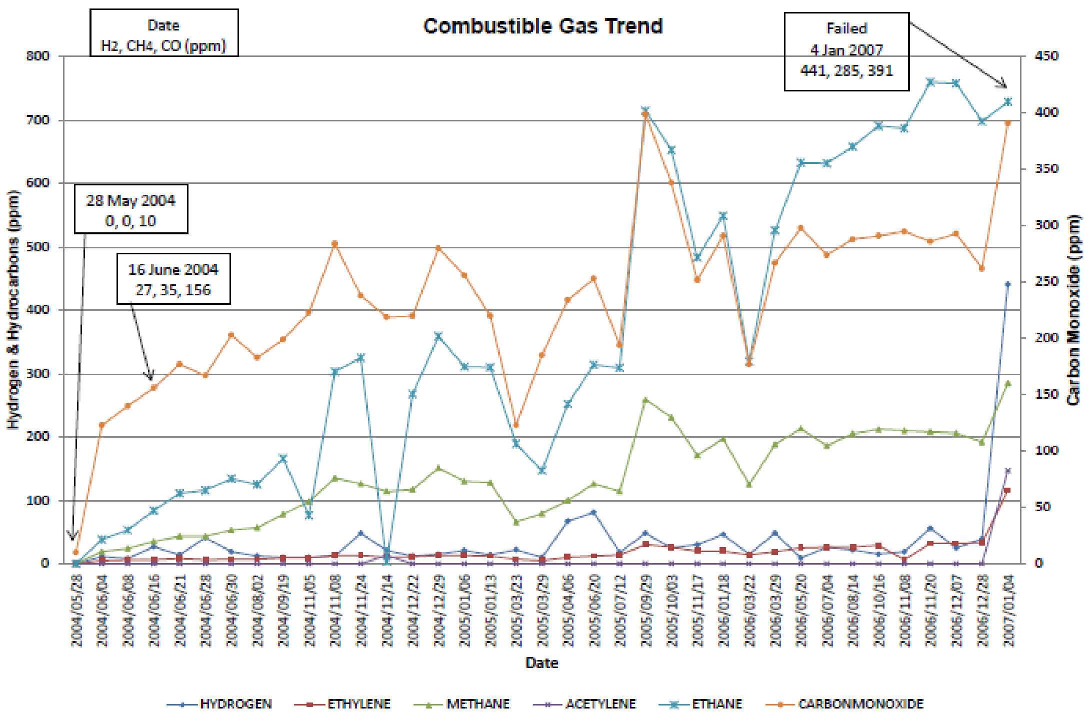


Figure 6-28: Combustible Gas Trend – Case Study G

R-Value

It is very clear from figure 6-29 that the R-values started moving out of normal state very soon after the commissioning of the transformer. It increased constantly until the failure on the 4 January 2007.

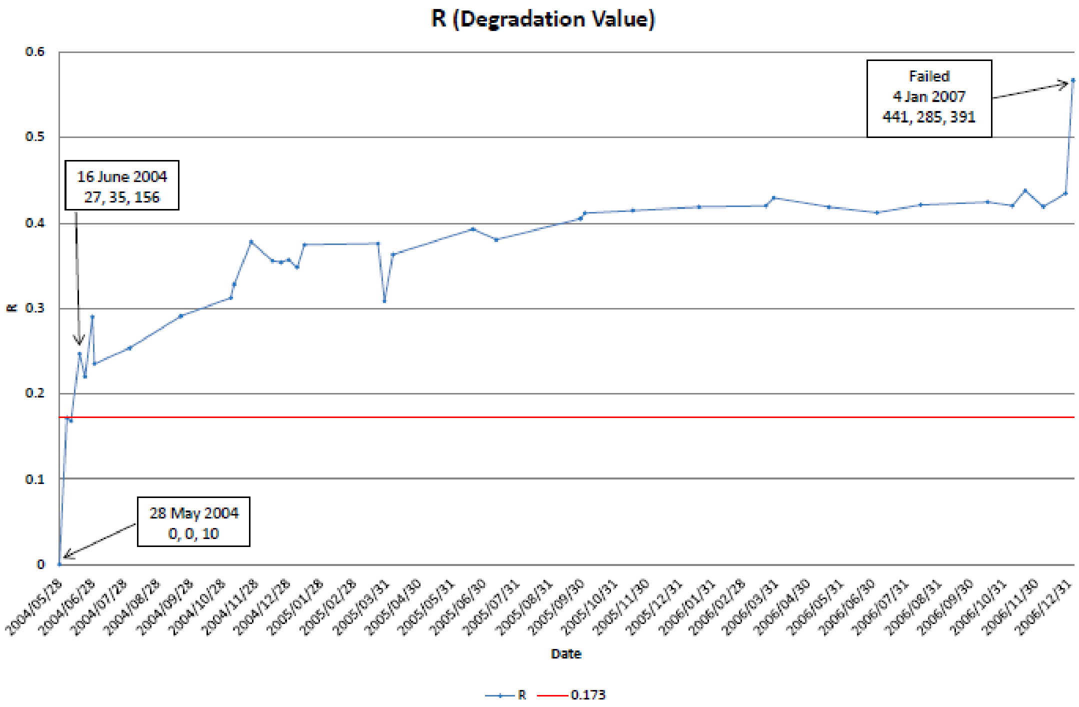


Figure 6-29: R-Value - Case Study G

Case Study G: Summary of Results

This case study provides a clear indication of the effectiveness of the LEDT in detecting change in transformer state from normal to defective. The defective state trigger was received at least two and a half years before the failure. This case study supports the theory that hydrogen is related to energy levels as the trend moved up the % CH_4 axis the levels of hydrogen remained low. This was supported with low levels of ethylene and acetylene.

6.2.7. Case H: 220 MVA (16.5 kV/400 kV, YOM: 1985) GSU Transformer Failure

Background [Coetzee1]:

On the 27 June 2000, this GSU transformer tripped after being in commercial operation for 5 days. The trip was attributed to a red-phase fault, which tripped on overall differential protection, restricted earth fault and Buchholz relay protection. The red-phase bushing had ejected out of its turret causing an oil fire. The automatic fire emulsifier system operated and partly contained the fire.

The transformer has been a spare since 1985 and was installed in two other units in January 1993 and the beginning of 1994 respectively. In April 1995 the transformer was taken to the workshop to dry out and for a modification to the LV bus bars where it was then returned back to the station in November 1995. However due to serious mechanical damage it was again transported to the Eskom workshop for repairs and in December 1995 the transformer was installed in another unit.

Due to increased gassing, the transformer was removed from service for an internal inspection which revealed a fault on the HV winding crossover. This was repaired and the transformer was reinstalled on February 2000.

LEDT:

From the LEDT in figure 6-30 it was found that the first sample after the repair was in the normal region as dated 20 December 1995. The second sample thereafter on the 25 June 1996 was in the defective region. Subsequent samples remained in this defective region indicating a severe imminent fault due to high levels of H_2. Before 14 November 1996 the oil was purified as indicated on the LEDT of figure 6-30.

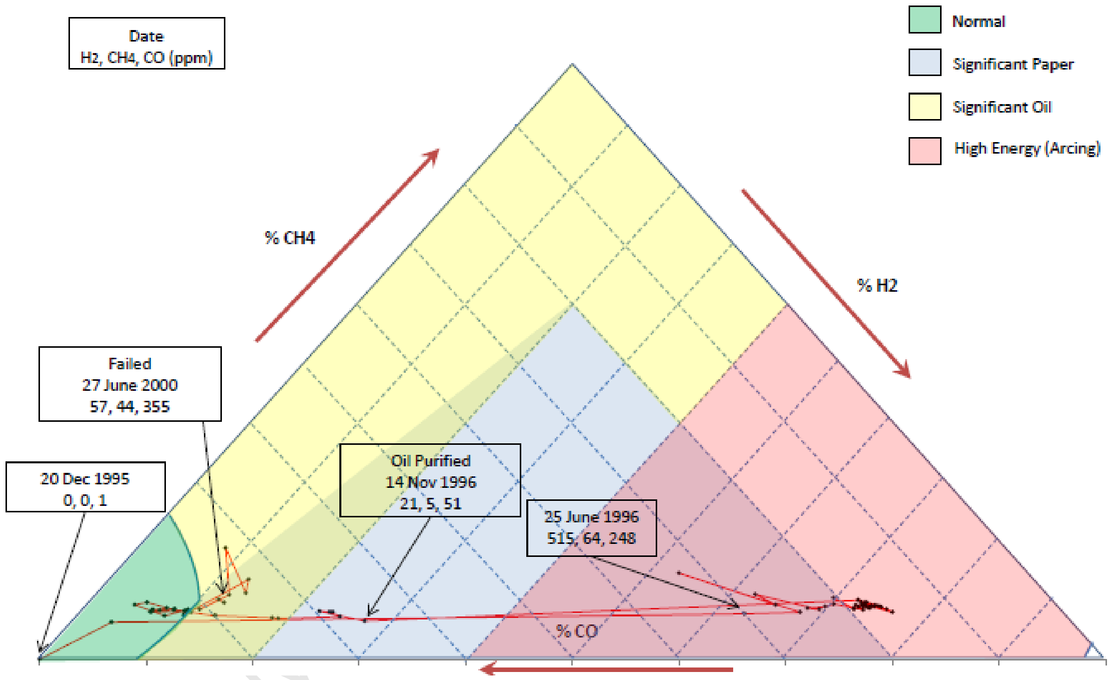


Figure 6-30: LEDT - Case Study H

Combustible Gas Trend:

Figure 6-31 is the combustible gas trend for case study H. After first installation on 25 December 1995 oil samples hereafter indicated high dissolved gas content with hydrogen at 1000 ppm and methane reaching 129 ppm in June 1996 samples. The carbon monoxide levels also increased since 1997 indicating possible insulation overheating. Since 1996 the transformer oil had been purified twice and approximately 10 000 litres of oil drained three times for inspections.

The results of the oil sample tests taken during the first half of 2000 revealed a steady build-up of hydrogen, methane, carbon dioxide and carbon monoxide while at the same time there was deterioration in the oil's dielectric strength. The transformer was taken out of service on 15 June 2000 for internal inspection. The windings were washed down with regenerated oil and the iron circuit tested clear. The transformer was filled with regenerated oil under vacuum and was returned to service on the 22 June 2000. This GSU transformer then failed on 27 June 2000

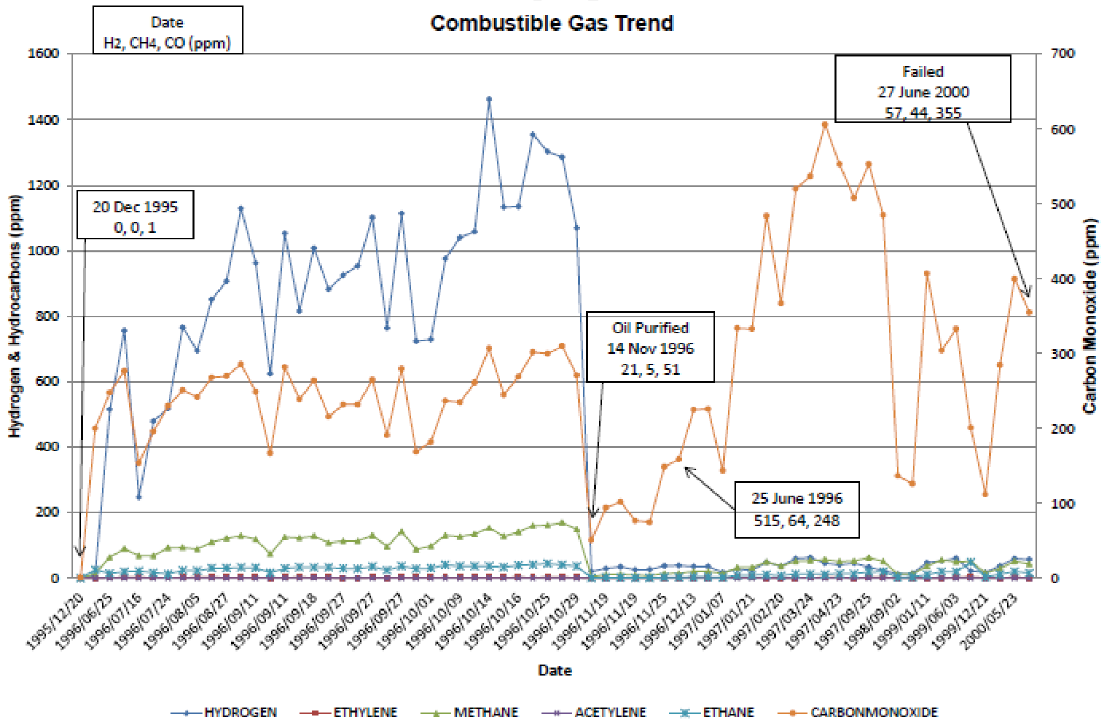


Figure 6-31: Combustible Gas Trend - Case Study H

R-Value:

The R-value trend in this case study is indicated in figure 6-32 where it is observed that from the initial installation there was a rapid move into the defective region. After the oil was purified on 14 November 1996 the R-values moved into the normal region until the 3 May 1999 when a defective trigger was received. This maintained itself until the failure on 27 June 2000.

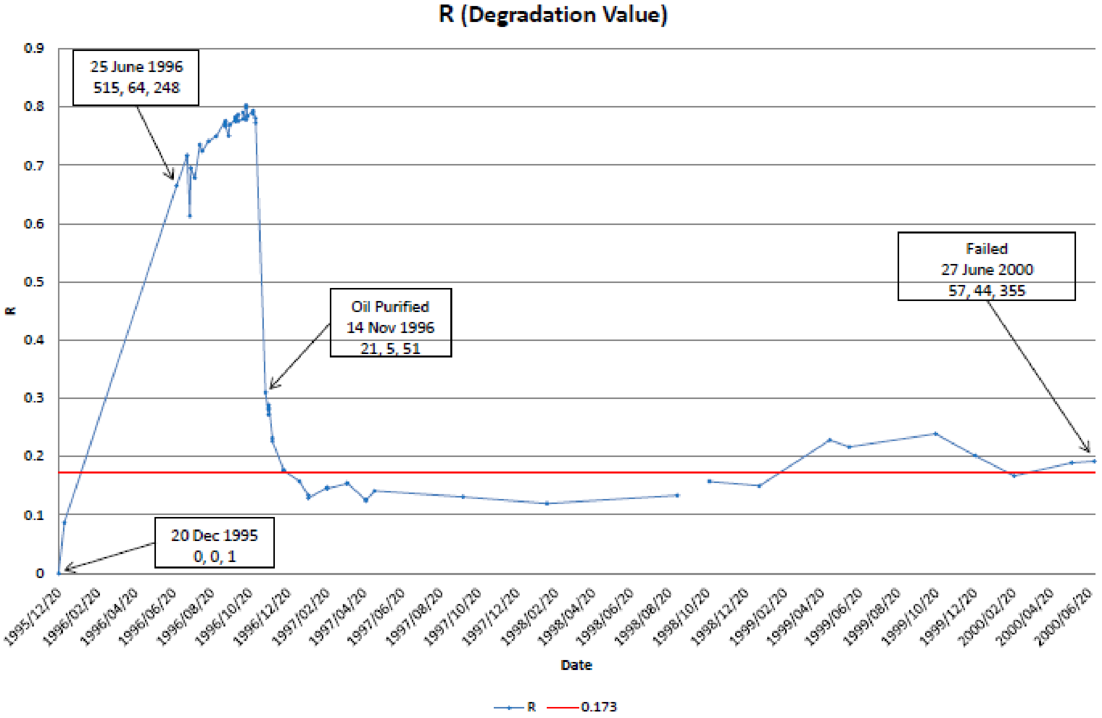


Figure 6-32: R-Value - Case Study H

Case Study H: Summary of Results

In this case study the initial oil sample recorded was in the normal region of the LEDT but by the third sample it had moved well into the defective range. The trend was along the %CO axis. The LEDT normal and defective regions correlated well with the oil sample results. Due to this transformer only been commissioned on the 22 June 2000 and failing on the 27 June 2000 there was no time or samples taken for any further triggers to be received by the LEDT. There R-value trend correlated well with the oil samples for dissolved gases.

6.2.8. Case I: 220 MVA (16.5 /400 kV, YOM: 1982) GSU Transformer Failure

Background [Mpepele1]:

On the 14th of May 2005 this GSU transformer failed with a fire on the white phase HV bushing. It was found that both the left and right PRVs had operated resulting in oil spillage into the bund area. The transformer tank was also significantly damaged with bulging and cracks. Inherently the transformer (and those of the same make) was identified to be suffering from poor internal oil flow and cooling, as well as LV winding and tail-lead overheating problem.

Internal inspection revealed that the blue phase HV winding lead was pulled out of the bushing damaging the bushing with evidence of a flash over between the main tank and the corona ring (Figure 6-33). All the bushings were damaged. Inspection of LV leads showed no signs of overheating.

Figure 6-33: Damage B phase HV Bushing

LEDT:

The LEDT for this case study is indicated in figure 6-34. It was found that the majority of the samples were within the normal region of the LEDT. There were two significant triggers received on 2 September 1999 and 30 October 2001. These however did not sustain the trend due to low levels of hydrogen although the methane levels were slightly elevated. The failure on the 14 May 2005 thus was not effectively picked up by the LEDT.

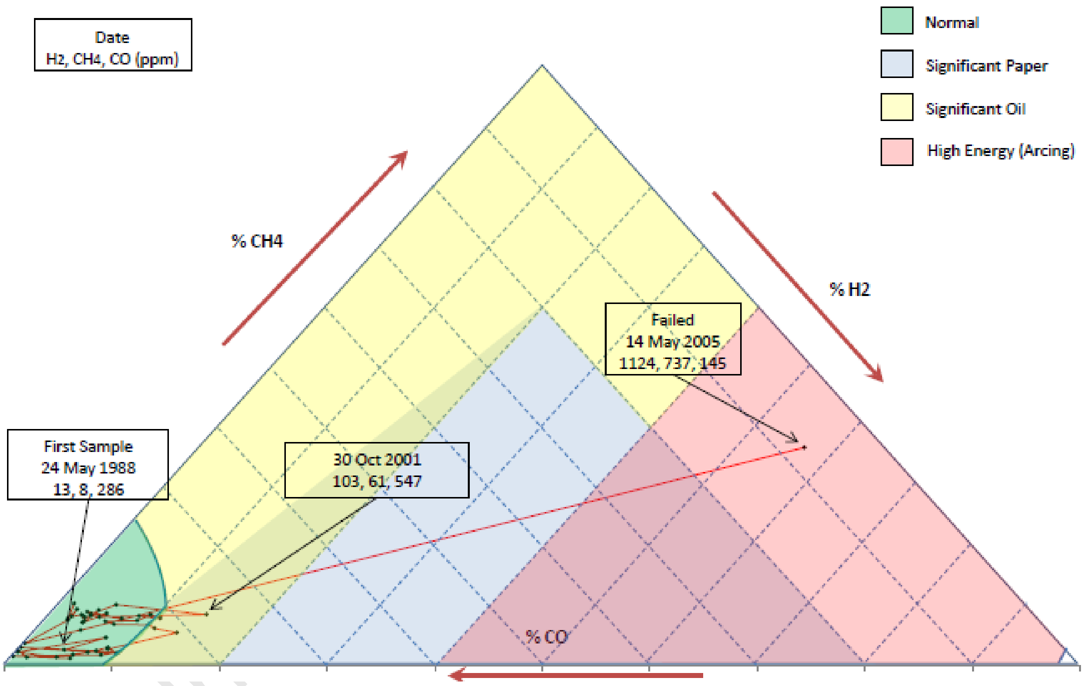


Figure 6-34: LEDT - Case Study I

Combustible Gas Trend:

The combustible gas trend is displayed in figure 6-35. The first sample taken on the 24 May 1988 was in the normal region with low levels of dissolved gases. The trigger on 30 October 2001 indicated elevated levels of carbon monoxide with elevated levels of hydrogen and methane. These values however did not sustain.

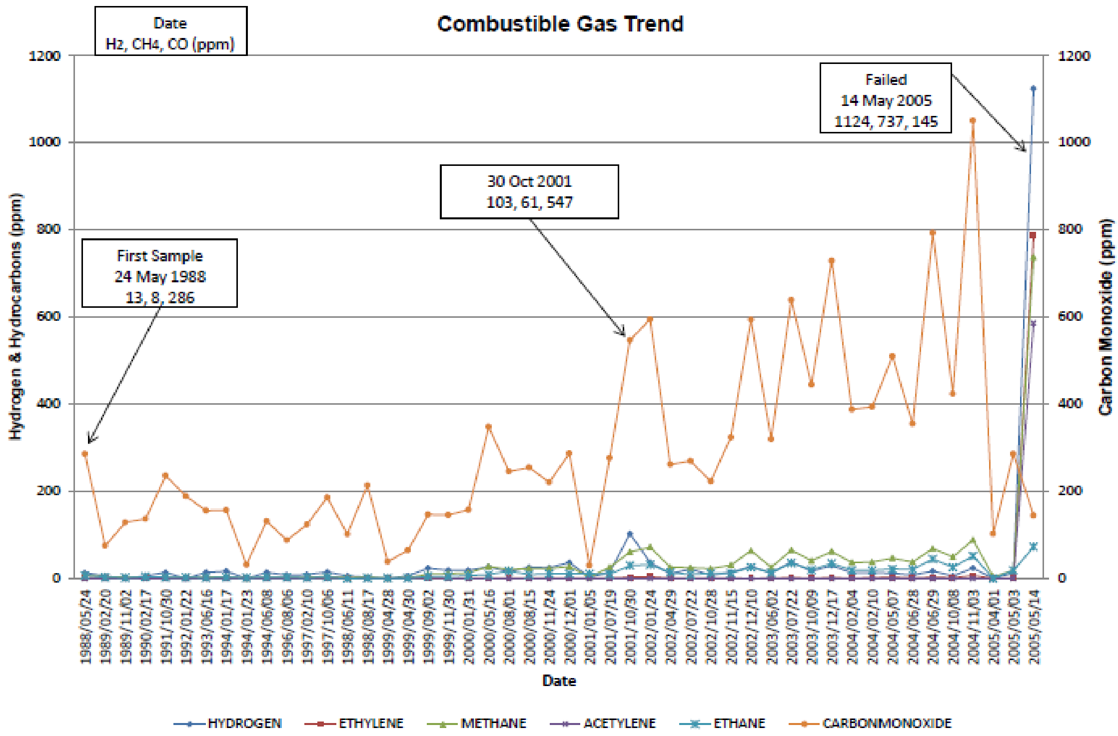


Figure 6-35: Combustible Gas Trend - Case Study I

R-Value:

R-values are indicated in figure 6-36 which clearly indicate the trigger on 30 October 2001 with no other significant out of normal state.

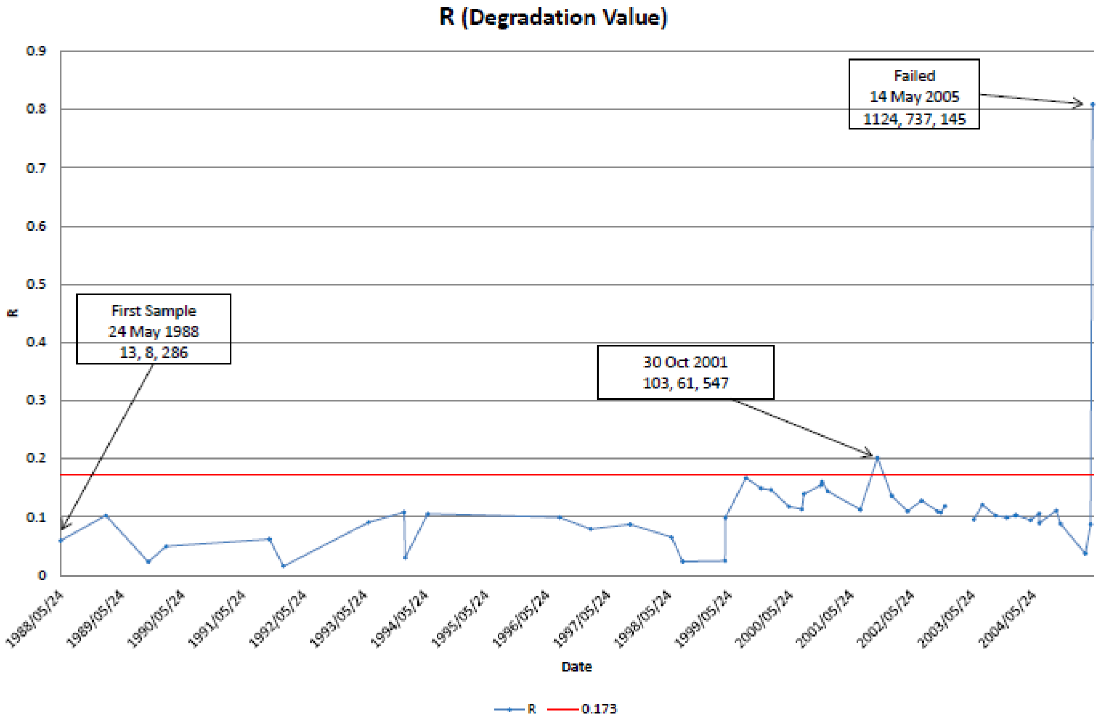


Figure 6-36: R-Value - Case Study I

Case Study I: Summary of Results

In this case study I almost all the oil results recorded were in the normal region of the LEDT. There were no significant sustained trigger identified for this case study. From the inspection of the LV windings it was found that there were no signs of overheating thus consistent with lower levels of hydrogen. There was however evidence of corona with the HV windings and the tank. This was consistent with the elevated levels of methane. The carbon monoxide levels were on the high side towards the end at around 800 ppm. Thus even though there were slightly elevated levels of methane these were not high enough to move the LEDT to the defective region.

6.2.9. Case J: 700 MVA (20/300 kV, YOM: 1984) GSU Transformer Failure

Background [Rodseth1]:

On the 30th September 2005 this 700 MVA GSU transformer tripped on Buchholz protection. From the fault recording there was indication that there was a problem with the White Phase HV winding. The internal inspection confirmed this as indicated in figure 6-37 with damage on the HV leads.

Figure 6-37: Damage to HV Leads

LEDT:

Figure 6-38 provides the LEDT representation for case study J where it is observed that almost all of the dissolved gas results were within the normal region. On further investigation it was found that there was a step change in the movement from 3 April 2002 where the samples then focused around the area close to the limit for normal state. The first trigger was received on the 24 September 2005 with ppm values of 107 ppm, 68 ppm and 770 ppm for hydrogen, methane and carbon monoxide respectively. This trigger was due to the influence of θ, which adjusted the LEDT for compensation of the energy levels. This trigger was however only one week before the failure which occurred in the 30 September 2005

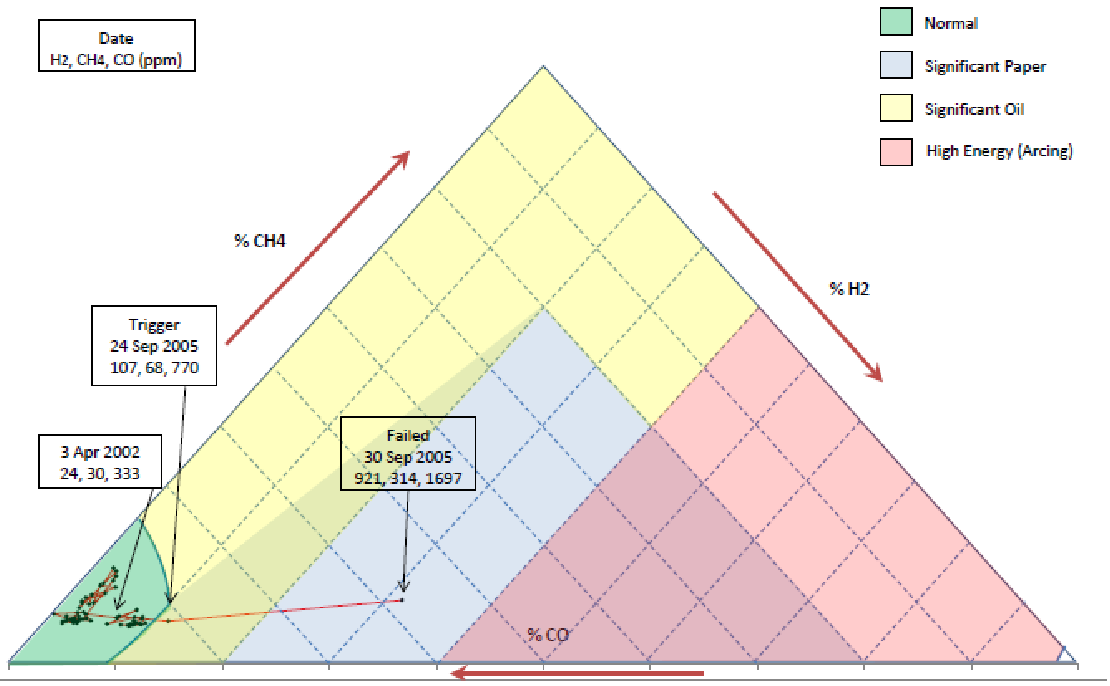


Figure 6-38: LEDT - Case Study J

Combustible Gas Trend:

The combustible gas trend in figure 6-39 indicates high levels of carbon monoxide with elevated levels of hydrogen and methane. Although the levels of hydrogen and methane were out of normal the trend did not display and drastic increases.

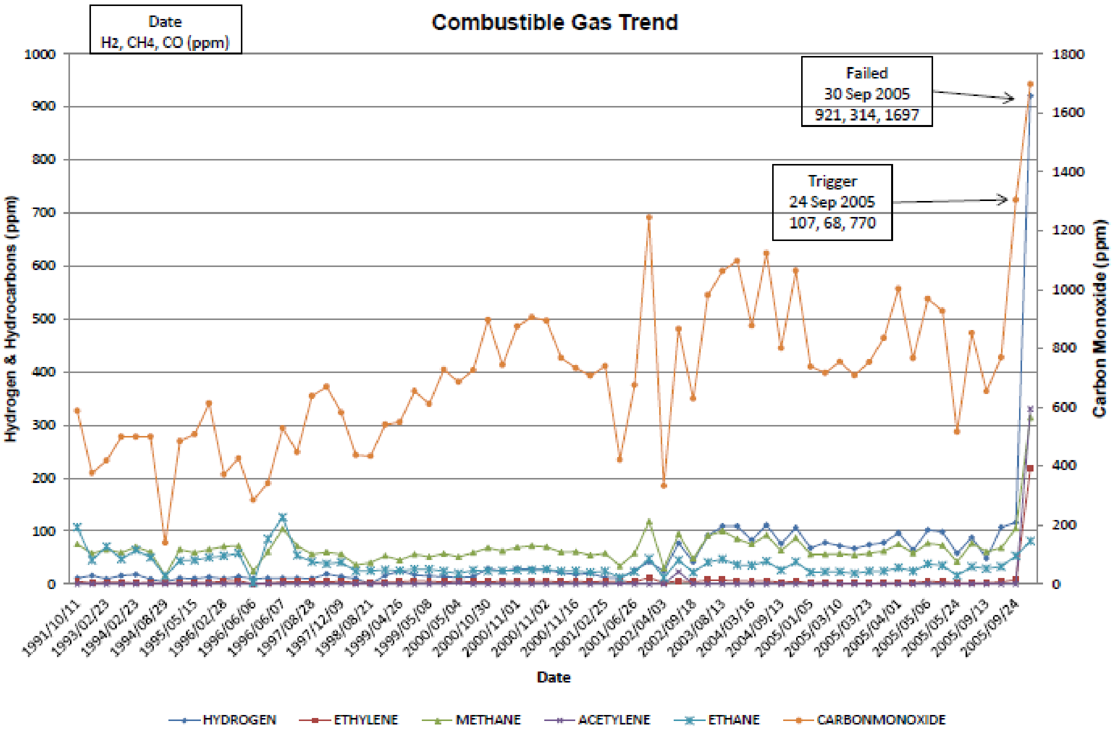


Figure 6-39: Combustible Gas Trend - Case Study J

R-Value:

From the R-Value trend in figure 6-40 it was clear that most of the oil samples were within the 0.173 limit except for the trigger on the 24 September 2005 (due to the influence of θ) and subsequent failure on the 30 September 2005.

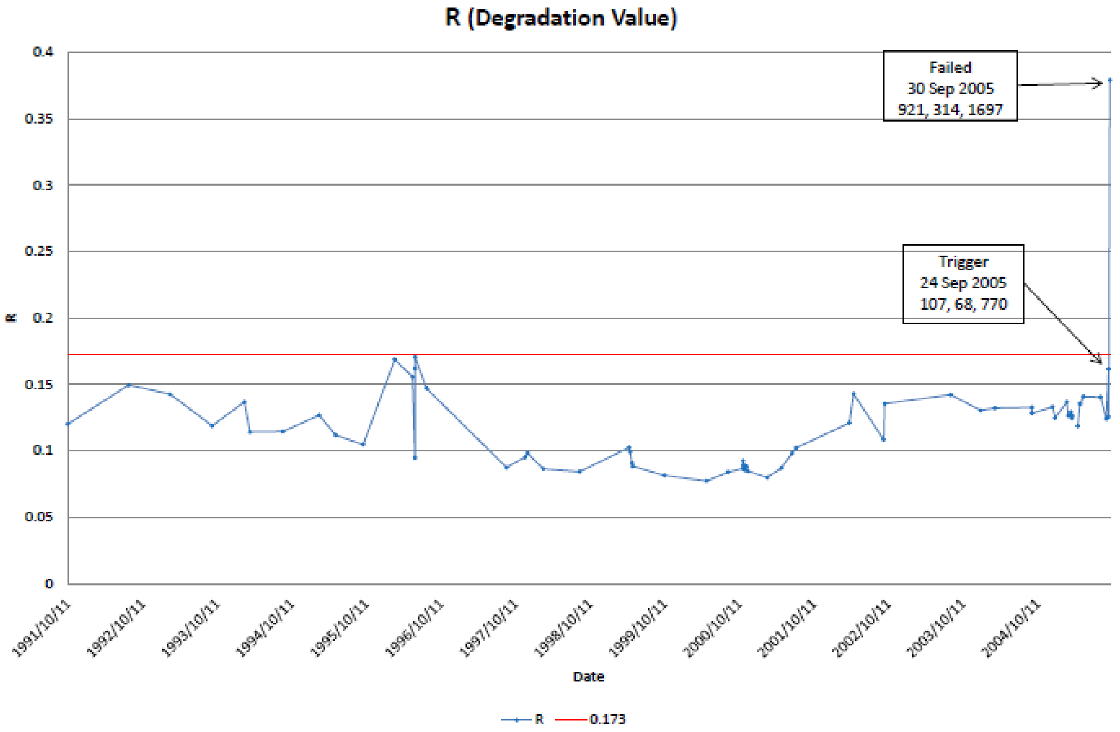


Figure 6-40: R-Value - Case Study J

Case Study J: Summary of Results

This case study introduces an interesting observation related to high levels of carbon monoxide. A large number of carbon monoxide values in the case study were greater than 600 ppm. Although the hydrogen and methane levels were elevated, the levels were not high enough for an effective trigger due the high levels of carbon monoxide. In this case the trigger into the defective region was only received a week before the failure. It was also observed that the θ value also had a significant role in providing the first trigger due to the influence of energy and hydrogen levels.

6.2.10. Case K: 700 MVA (20/300 kV, YOM: 1986) GSU Transformer Failure

Background [Pillay1]:

On Sunday, 27 February 2005, this GSU Transformer tripped on Generator Differential protection, HV restricted earth fault protection and Buchholz protection. No external damage was noted but the internal inspection of the active parts of the transformer revealed heating around the top of the HV windings and exit leads which caused accelerated paper degradation. This damage was evident in figure 6-41.

Figure 6-41: Damage to HV Winding

LEDT:

The LEDT for this case study is depicted in figure 6-42. Most of the samples were in the normal region until the first trigger which was received on the 13 August 2003 with hydrogen at 116 ppm, methane 56 ppm and carbon monoxide at 937 ppm. All points thereafter were in the defective region until failure occurred on 27 February 2005.

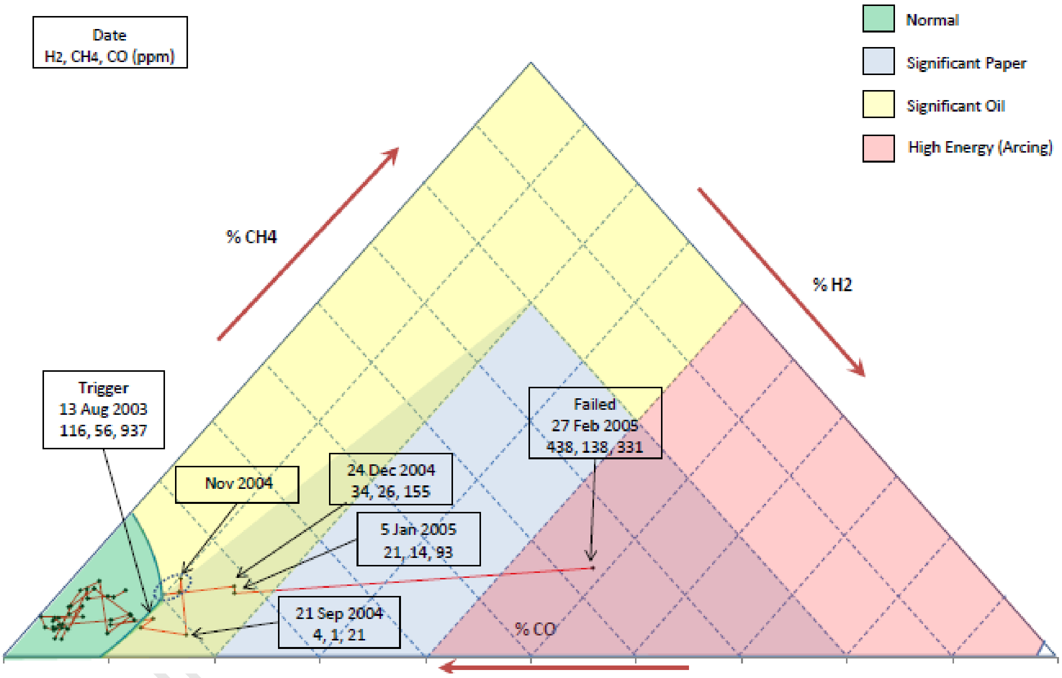


Figure 6-42: LEDT - Case Study K

Combustible Gas Trend:

From the combustible gas trend in figure 6-43 it was observed that the methane levels were always high (within 50 ppm) but maintained this level for a long period. In 2002 it was noticed that the hydrogen levels started to increase.

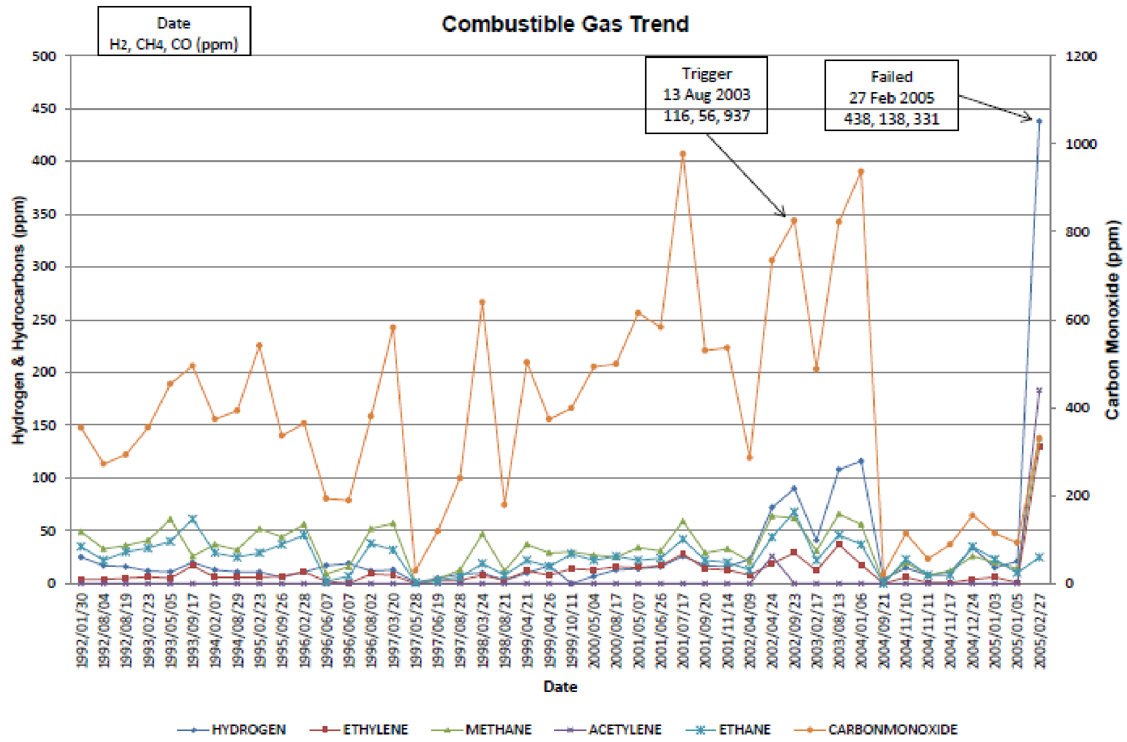


Figure 6-43: Combustible Gas Trend - Case Study K

R-Value:

From figure 6-44 it was observed that the R-values were mostly under the limit until the trigger received on the 13 August 2003 due to the influence of the θ value. The next trigger was received on 21 September 2004. The values of hydrogen, methane and carbon monoxide were 4 ppm, 1 ppm and 21 ppm respectively.

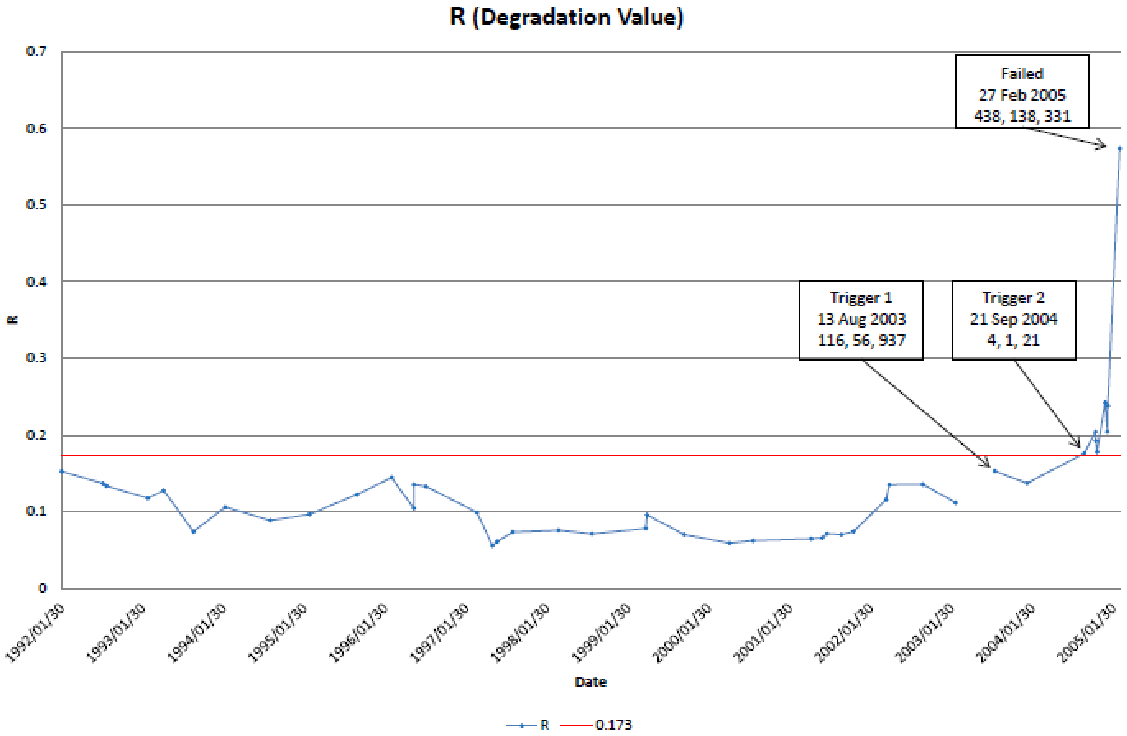


Figure 6-44: R-Value - Case Study K

Case Study K: Summary of Results

In this case study most of the oil results recorded was in the normal region of the LEDT. The first trigger was received due to the influence of θ which was triggered by the increase in hydrogen levels. The carbon monoxide levels were high initially but then drastically decreased. The transformer oil was replaced with virgin oil during a major outage August/September 2004 as a result of the rapid deterioration of the oil quality (acidity was high, interfacial tension and electrical strength was low). The results obtained in the LEDT trend were consistent with the dissolved gas normal and defective regions. The first trigger was received at least one and a half years before the failure. The second trigger was recorded 5 months before the failure.

6.2.11. Case L: 100 MVA (13.2/132 kV, YOM: 1976) GSU Transformer Failure

Background [Sibiya1]:

A 100 MVA GSU transformer failed on 28 November 2001, resulting in the electrical protection and pressure relief device operating. On site, internal inspection revealed tiny copper particles distributed over the transformer connections, insulation and windings especially in the area of the C phase winding.

Internal inspection of the transformer revealed distortions on the C phase windings. There were black spots on the paper insulation of the tap changer leads with damage to the support structure of the delta connection. A loose clamping bolt on the C phase LV winding was found with winding spaces in the damaged area showing marks of "hammer effect". Figure 6-45 provides a picture depicting the failure on the C phase LV winding. Evidence of an inter turn failure was present. One of the frame bolts on the C phase LV side connection was loose, and mechanical clamping device marks were noticed. This may have resulted in insufficient torque being applied during the assembly process and vibration was then transferred to the windings causing insulation failure and the inter turn fault.

Figure 6-45: Damage C Phase LV Winding

Combustible Gas Trend:

Figure 6-46 provides a depiction of the dissolved gas trends for the transformer to the last date before the incident. After the incident, the results were as follows; hydrogen 993 ppm, methane, 506 ppm, ethylene 705 ppm, ethane 66 ppm and acetylene 448 ppm. It was found that the hydrocarbon gases were not at elevated levels but the carbon monoxide levels were high.

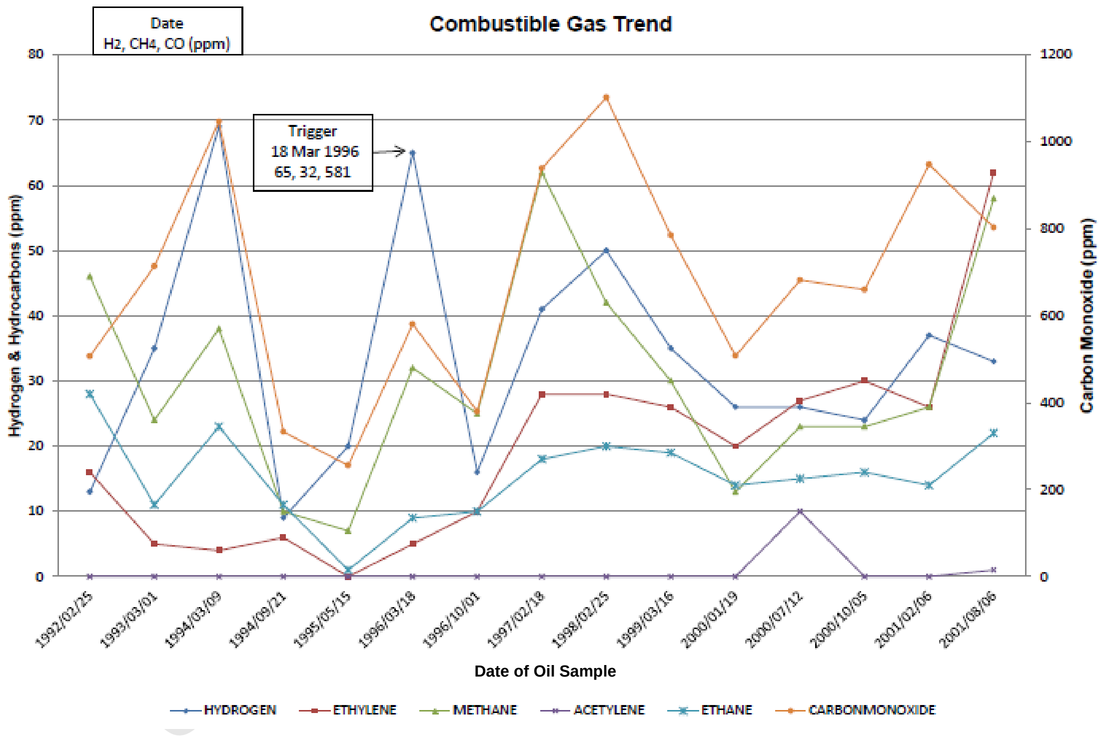


Figure 6-46: Combustible Gas Trend - Case Study L

LEDT:

Figure 6-47 is the LEDT representation of this case study. In this case study all the points are within the normal region. There was only one point that bordered the normal limit as influenced by θ. There were no significant triggers received before the failure. Although the hydrogen value was 65 ppm the high carbon monoxide levels diluted its effect.

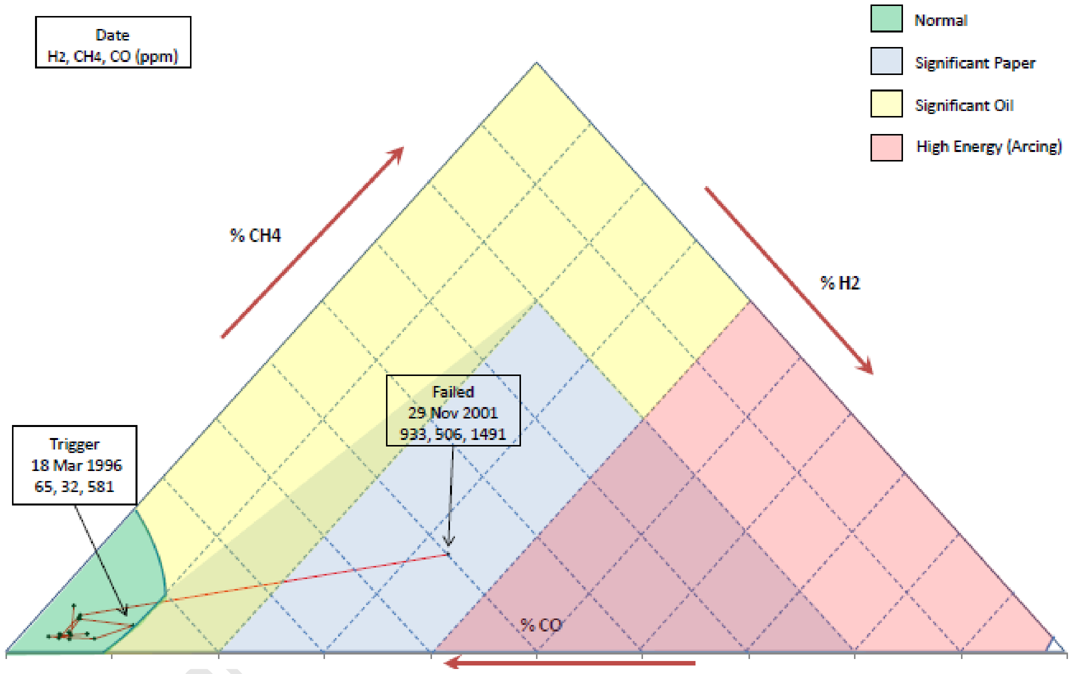


Figure 6-47: LEDT - Case Study L

R-Value

Figure 6-48 is the R-value plot for this case study. All sample points before the incident are within the limits.

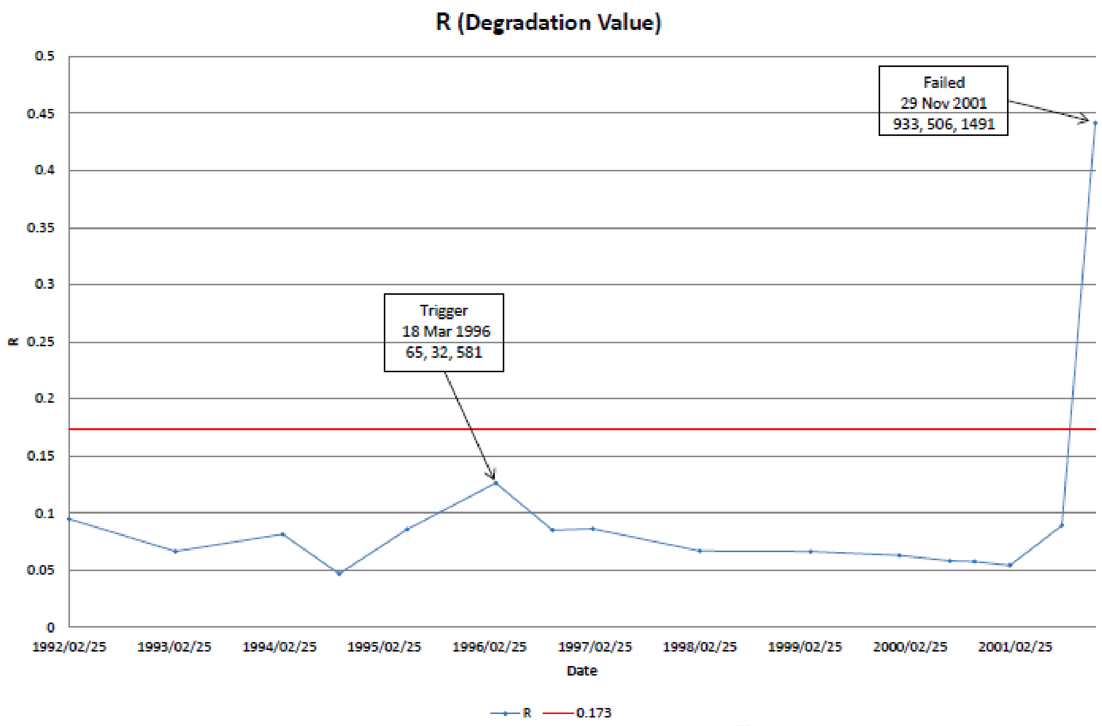


Figure 6-48: R-Value - Case Study L

Case Study L: Summary of Results

The transformer was operated on a cyclic loading of just one hour for every two hours due to the operating regime (water releases) of the hydro station for a few years before the incident. This may have masked and prolonged the failure. It was noted that this failure occurred when the power station unit was running as base load due to high water levels. The transformer was thus fully loaded for at least one month before the incident occurred.

It must also be noted that the levels of dissolved gases were also not at very high levels. These would just enter within defective levels and with the next oil sample fall back with limits.

It was interesting to note that this case study was based on the GSU transformer that was referred to in the introduction. Although from the results the LEDT would still have not provided an effective trigger of the imminent failure, the author now understands the impact of transformers operating in an intermittent loading cycle which may remove the sensitivity of dissolved gas analysis. This once again supports the technological advancement of continuous online monitoring of dissolved gases.

6.3. SUMMARY

From the 12 case studies analysed there were effective warning triggers on 10 transformers. This is summarised in table 6.3

Table 6.3: Summary of Case Study Findings

Case Study	Date of First Trigger	Date of Failure/Taken Out	Period Before Failure
A	13 November 2002	9 May 2008	5 years 6 months
B	8 October 2001	14 November 2004	3 years
C	7 February 2000	22 December 2004	4 years 10 months
D	22 December 2004	15 May 2005	5 months
E	24 April 2003	30 May 2004	1 year
F	22 June 2002	16 May 2004	11 months
G	16 June 2004	4 January 2007	2 years 6 months
H	22 June 2000	27 June 2000	5 days
I	No Trigger	14 May 2005	
J	24 September 2005	30 September 2005	6 days
K	21 September 2004	27 February 2005	5months
L	No Effective Trigger	28 November 2001	

It was found that the initial results of normal state correlated with the LEDT normal region. When a defective trigger was received, further results of defective state were consistent with the LEDT.

Another positive aspect observed was that even though the combustible gas trends were erratically increasing and decreasing cyclically the LEDT was relatively insensitive to these changes such as to provide an increasing trend. It is however emphasised that accurate and reliable dissolved gas samples must be utilised for condition assessment. On-line monitors with erratic data must always be followed up by routine tin samples to confirm the reliability of the data.

There was also an increasing trend of the R-value with time as the levels of combustible gases increased. In some of the case studies, it was observed that even though there was a decrease in the levels of combustible gas trends, the R-value trend still maintained the upward trend without major decreases. In other cases it was identified that although some of the R-values were below the 0.173 limit, due to the effect of θ, on the LEDT some points were in the defective region. This emphasises the importance of using the θ compensation on the LEDT plot.

Case study G supported the theory that hydrogen is related to energy levels as the trend moved up the % CH_4 axis the levels of hydrogen remained low. This was supported with low levels of ethylene and acetylene.

A significant finding from the case studies was that although at times the hydrogen and methane levels were elevated, the levels were not high enough for an effective trigger due the levels of carbon monoxide being above 600 ppm.

6.3.1. Validation of LEDT to IEC 60599 Codes and Duvals Triangle

As validation of the LEDT, a comparison was made to the IEC 60599 codes and Duval's Triangle. The last 5 dissolved gas samples prior to failure or being removed from service were used for this assessment. Table 6.4 provides details of the results.

Table 6.4 Validation of LEDT with IEC Codes and Duvals Triangle

CASE STUDY	IEC CODES	DUVAL	LEDT	FAILURE	MINIMUM DP			FURAN (DP)
					LV	HV	LEAD	
A	No diagnosis	T2	Abnormal - Lower Centre	Elevated gas levels with damaged leads				440
B	No diagnosis	T2/T3	Abnormal - Lower Left	Damage to interturn fault C phase HV winding	445	543	438	300
C	No diagnosis	T1	Abnormal - Lower Left just outside normal limit	Insulation breakdown in HV winding	260	229	118	280
D	T3	T2/T3	Abnormal - Lower Left	Interturn fault on the C phase HV winding.				332
E	T1	T2	Abnormal - Lower/middle Left	interturn fault on B phase LV winding				750
F	No diagnosis	T3	Abnormal - Upper middle	Winding Leads				127
G	T1	T1/T2	Abnormal - middle Left	Interturn fault on HV winding	299	437	489	290
H	T1	T1	Abnormal - Lower Left just outside normal limit	flashover of the red phase HV lead to the core clamp		484		117
I	T1	T1	Normal	Damage to B phase HV winding				251
J	No diagnosis	T1	Abnormal due to θ	Damage to B phase HV winding				310
K	T1	T1/T2	Abnormal - Lower Left	Insulation breakdown between LV	233	219	553	525
L	No diagnosis	T3	Normal	Interturn fault on LV winding				320

From the results in table 6.4 it can be seen that the LEDT method compares very favourably to Duvals triangle in providing an abnormal state. In the two cases (I and L) where the LEDT did not indicate an abnormal state this was solely due to the high levels of carbon monoxide. When compared to the IEC 60599 codes, it is found that the LEDT method provided a diagnosis for majority of the transformer states as opposed to the IEC 60599 which had 6 "No diagnosis" states.

Duval Triangle 5 was formed more specifically by faults of high temperature to provide more information about thermal faults in paper and in oil [Duval5]. This method identifies only possible cabonisation of the paper which is based on the high temperature of the fault. Duval Triangle 4 was formed more specifically by faults of low energy PD, T1 and T2 with detection of possible carbonising of paper [Duval5]. Both Duval 4 and 5 is composed of dissolved gases from the byproducts of oil and the involvement of paper is inferred from the assessment of the fault temperatures causing carbonising of the paper. The LEDT method was created to identify a change of state from normal to abnormal based on the degradation of insulation (oil + paper). One of the key components of the LEDT is carbon monoxide (CO) which is one of the byproducts of paper degradation thus providing a "direct" measure of the influence of paper degradation. Thus when the LEDT provides a trigger of abnormal state it takes into account the degradation of paper and provides some indication that the failure mechanism is one of low or high energy.

6.3.2. Comparison of LEDT to DP and Furans

A comparative analysis was also conducted between the degree of polymerisation (DP)/furan and the results of the LEDT. DP results were only available on some of the transformers. From Table 6.4 it is found that the range of DP for the HV windings was from 219 to 543 and for the LV windings from 233 to 445. The furan results range from 117 to 750 with an average of 336. Due to the number of samples no significant inferences can be formed between the LEDT and DP or Furan results. One of the findings in terms of case F, the furan predicted DP was 127 and the LEDT was in the upper middle region indicating significant movement in the LEDT for a low predicted DP value.

6.3.3. Validation of LEDT as an Asset Management Tool

One of the proposed distinct advantages of the LEDT is the use as an asset management tool to assess the risky transformers from a fleet of transformers in terms of insulation degradation. The ability to assess normal state of the transformer is validated below. A comparison was made to the benefits of utilizing the LEDT in conjunction with the Duval's Triangle and IEC 60599 codes. The following case study is a 65 MVA GSU transformer for a gas-fired power station.

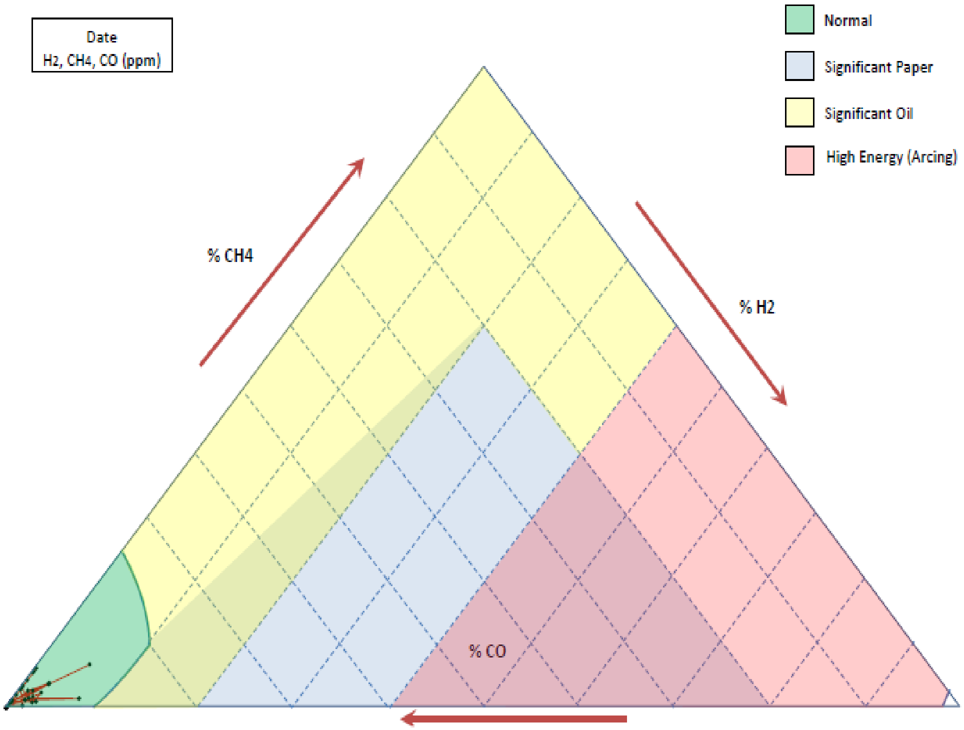


Figure 6-49: LEDT 37 Year Old 65 MVA GSU Transformer

This transformer was commissioned in 1976 with a moderate load factor. The history of tin oil samples were recorded from 1994 to present. The LEDT in figure 6-49 indicates that the transformer is still operating in the normal region.

The Duval representation as presented in figure 6-51 indicate that the transformer has been operating in the T2 and T3 regions indicating progression to a thermal fault greater than 700°C.

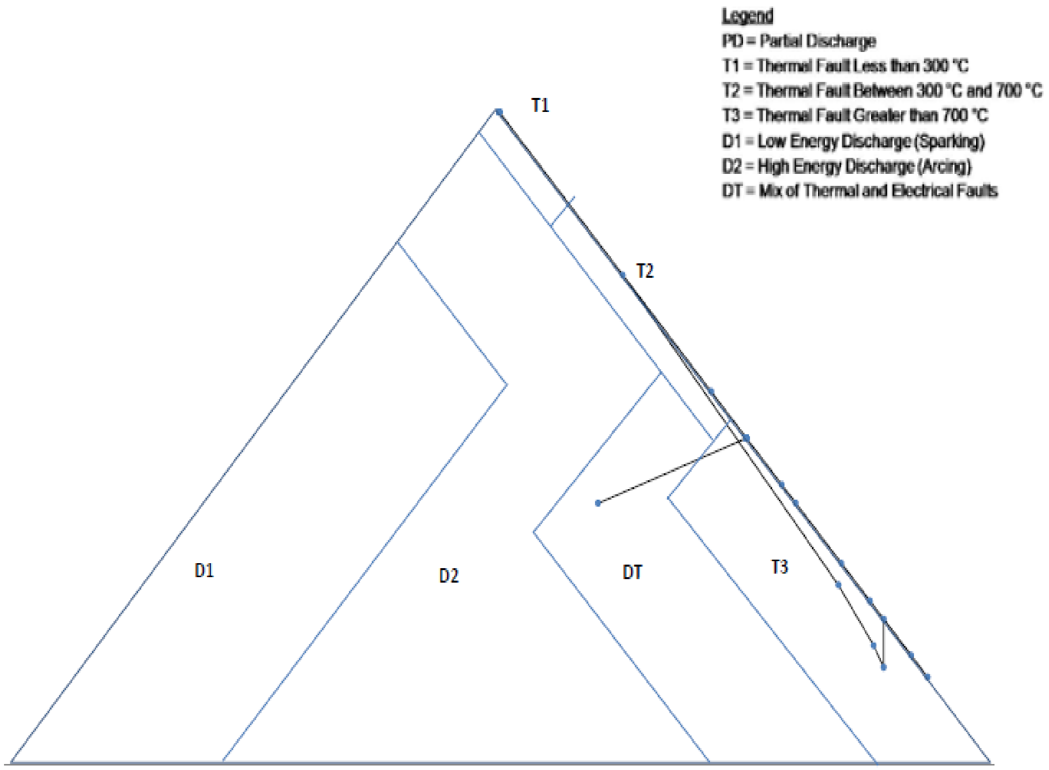


Figure 6-50: Duval 37 Year Old GSU Transformer

A closer analysis of the dissolved gas values reveal a 90% typical values of 5 ppm for hydrogen, 6 ppm for methane, 13 ppm for ethylene and 0 ppm for acetylene. A comparison to the IEC 60599 codes revealed a condition of T3 indicating a condition of thermal fault greater than 700°C.

The transformer is presently 37 years old and is still operating satisfactorily. The LEDT thus from an asset management perspective provides a realistic tool for identifying the general condition of the transformer fleet.

CHAPTER 7

GENERAL DATA ANALYSIS AND DISCUSSION

7.1. INTRODUCTION

Chapter 6 provided a detailed analysis of the data when the LEDT was applied to 12 case studies. What was evident from the case studies was that the LEDT does provide meaningful trends that can be used to identify a change from a normal state to that of the defective. These triggers on most of the case studies were well in advance of the failure.

Chapter 7 provides a detailed analysis and discussion of the results and findings from the general results as recorded within the database of oil sample dissolved gas results.

7.2. GENERAL ANALYSIS OF GROUPED DATA

Apart from the case studies a general analysis of the transformer-dissolved gases to discover any further relationships relevant to this study was performed. It is emphasised that this analysis is based on all the dissolved gas data and includes a significant number of transformers that either have failed or were removed from service.

This study was limited to GSU Transformers. The main reason for including this analysis was to validate the LEDT normal region and the hypothesis that as a trend moves futher away from the origin (towards centre of LEDT) the levels of the three dissolved gases hydrogen, methane and carbon monoxide would change accordingly to support higher energy and greater degradation that would result in a fault or failure.

7.2.1. Normal Region (R < 0.173)

The following investigation was made in identifying the dissolved gas values in ppm for oil samples that were within the 0.173 R-value limit. Figure 7-1 is a distribution of this region in the LEDT.

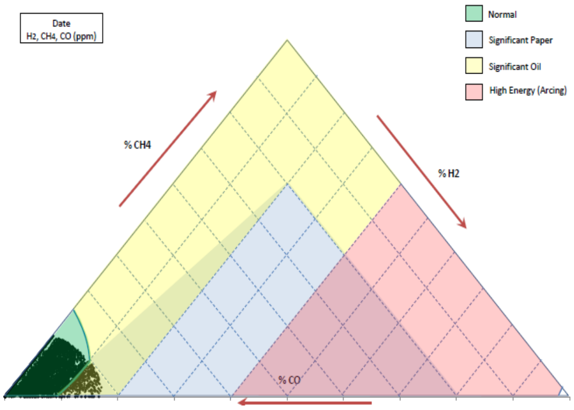


Figure 7-1: Distribution of R < 0.173

Table 7.1 provides a summary of the dissolved gas results where the maximum value of hydrogen was 116 ppm, with an average of 13 ppm and a standard deviation of 15 ppm. This is indicative that the majority of the hydrogen values in the normal region were within 0 ppm to 28 ppm. The maximum value of hydrogen at 116 ppm had a corresponding methane value of 56 ppm and carbon monoxide of 937 ppm. This is an interesting observation as it means that the carbon monoxide levels must be considered, as too high values could allow the hydrogen and methane trigger levels also to be high.

Table 7.1: Dissolved gas (ppm) statistics for oil samples < 0.173 R-Value

	H2	CH4	CO	C2H4	C2H2	C2H6	O2	N2	CO2
Minimum	0	0	1	0	0	0	0	3	0
Average	13	24	310	10	1	16	7574	39273	2235
Maximum	116	234	4337	2455	61	323	167074	450556	34701
Standard Dev.	15	32	292	40	3	26	7425	22209	2812
90% Typical Values	28	65	643	18	1	46	16566	60647	5228

The maximum value of methane was 234 ppm, with an average of 24 ppm and a standard deviation of 32 ppm indicating that the majority of the methane values in the normal region were within 0 ppm and 56 ppm.

The maximum value of carbon monoxide was 4337 ppm, with an average of 310 ppm and a standard deviation of 292 ppm indicating that the majority of the carbon monoxide values in the normal region were within 18 ppm and 602 ppm.

The average values for hydrogen, methane and carbon monoxide were 13 ppm, 24 ppm and 310 ppm respectively. This is equivalent to the percentage representation of 3.75 %, 6.92 % and 89.34 % for the three gases hydrogen, methane and carbon monoxide respectively.

When comparing the 90% typical values it was found that the percentage representation of hydrogen, methane and carbon monoxide was 3.80%, 8.83% and 87.36% respectively.

Taking the influence of θ within the LEDT it is found that a large number of samples, although within the R-value limit of 0.173, did fall outside the normal θ region. 90% of these samples were from transformers that have either failed or removed from service.

It was also noted that some of the maximum dissolved gas values like oxygen, nitrogen and carbon monoxide was extremely high. These maybe attributed to either problems in sampling, testing and recording of data. This highlights that fact that any sudden outlier sample must be analysed with care as these may not be a true representation of the condition of the transformer.

7.2.2. 0.1557 < R < 0.173

Due to the influence of high carbon monoxide values, table 7-2 provides a summary of dissolved gas values for R-values taken within 10% of the 0.173 trigger value which is 0.1557. Figure 7-2 provides a picture of this distribution.

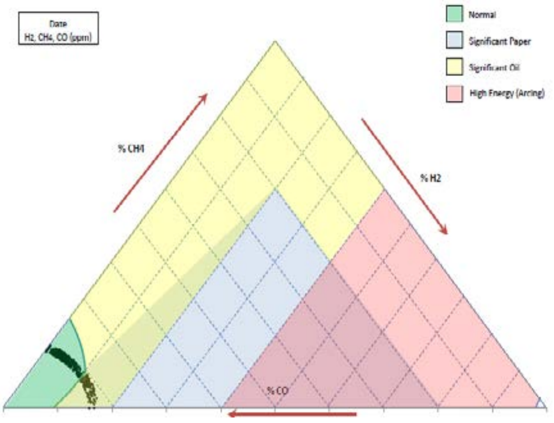


Figure 7-2: Distribution of 0.1557 < R < 0.173

The summarised dissolved gas results from Table 7.2 reveals a maximum value of carbon monoxide of 1246 ppm, an average of 304 ppm and a standard deviation of 252 ppm thus indicating a distribution of within 52 ppm to 557 ppm.

The 90% typical values reveal the percentage representation of hydrogen, methane and carbon monoxide as being 5.11%, 14.27% and 80.62% respectively.

Table 7.2: Dissolved gases for 0.1557 < R < 0.173

	H2	CH4	CO	C2H4	C2H2	C2H6	O2	N2	CO2
Minimum	0	0	5	0	0	0	0	3	31
Average	19	47	304	17	1	43	5021	37979	2741
Maximum	107	234	1246	242	20	323	36423	187555	19686
Standard Dev.	17	45	252	36	2	49	4741	20883	2812
90% Typical Values	43	120	678	37	0	109	10701	61671	6328

7.2.3. 0.173 < R < 0.5

An assessment was then made on the distribution of dissolved gas samples in the abnormal region where R was within 0.173 and 0.5. This distribution of oil samples in the LEDT is depicted in figure 7-3.

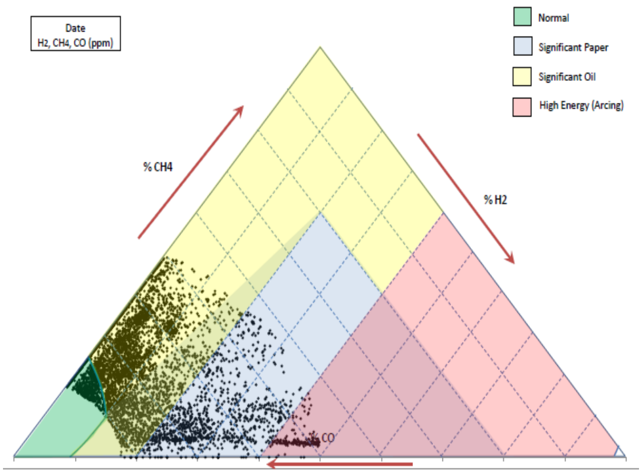


Figure 7-3: Distribution of 0.173 < R < 0.5

Table 7.3 presents the corresponding dissolved gas analysis where the maximum value of hydrogen is now 993 ppm with an average of 38 ppm and standard deviation of 56 ppm. The range of hydrogen was from 0 ppm to 94 ppm. Methane had a maximum value of 573 ppm with an average of 70 ppm and standard deviation of 66 ppm. The range of methane was from 4 ppm to 136 ppm. The maximum carbon monoxide value was 1916 ppm with an average of 224 ppm and standard deviation of 174 ppm. The range of carbon monoxide is from 50 ppm to 398 ppm. There were also elevated levels of ethylene and acetylene at these levels suggesting severe thermal heating.

Table 7.3: Dissolved gas for 0.173 < R < 0.5

	H_2	CH_4	CO	C_2H_4	C_2H_2	C_2H_6	O_2	N_2	CO_2
Minimum	0	0	2	0	0	0	0	3	0
Average	38	70	224	36	2	78	4484	36536	2317
Maximum	993	573	1916	1514	448	1356	226654	324896	46461
Standard Dev.	56	66	174	63	11	109	6513	22107	2366
Typical 90% Values	74	166	457	119	3	189	9283	62091	5294

The 90% typical values reveal the percentage representation of hydrogen, methane and carbon monoxide as being 10.62%, 23.82% and 65.57% respectively. For the average values for hydrogen, methane and carbon monoxide (38 ppm, 70 ppm and 224 ppm respectively) the equivalent percentage representation was 11.45 %, 21.08 % and 67.47 % respectively. This indicates a significant increase in the percentage makeup of hydrogen and methane values with a decrease in the percentage of the carbon monoxide. It was one again noted that the majority of these values were from transformers that were removed from service. This is evident from figure 7-5 which is a representation of the sample values from transformers that are presently in service.

7.2.4. R > 0.5

A final assessment in this regard was made for R > 0.5 covering the remaining points in the triangle. This was associated with high levels of degradation. Figure 7-4 is a picture of the distribution of these points in the LEDT.

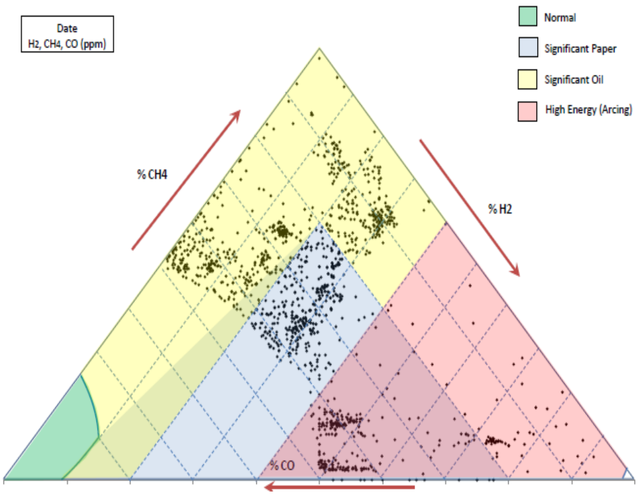


Figure 7-4: Distribution of R > 0.5

From the dissolved gas analysis in table 7.4 it was observed that the maximum value of hydrogen was 3681 ppm with an average of 154 ppm and standard deviation of 205 ppm. The corresponding range for hydrogen was from 0 ppm to 359 ppm. Methane had a maximum value of 6790 ppm with an average of 299 ppm and standard deviation of 404 ppm. The range of methane was 0 ppm to 703 ppm. Carbon monoxide levels recorded a maximum value of 1127 ppm with an average of 172 and standard deviation of 182. The range of carbon monoxide was 0 ppm to 254 ppm.

Table 7.4: Dissolved gas for R > 0.5

	H2	CH4	CO	C2H4	C2H2	C2H6	O2	N2	CO2
Minimum	0	0	0	0	0	0	49	1032	2
Average	154	299	172	282	7	132	3657	24958	1680
Maximum	3681	6790	1127	2960	883	1489	32514	78810	9797
Standard Dev.	205	404	182	364	51	178	3788	16838	1625
90% Typical Values	332	758	513	669	4	439	7406	48808	3517

For R-values greater than 0.5 the average values for hydrogen, methane and carbon monoxide were 154 ppm, 299 ppm and 172 ppm respectively, which was equivalent to the percentage representation of 24.64 %, 47.84 % and 27.52 % respectively. The 90% typical values reveal the percentage representation of hydrogen, methane and carbon monoxide as being 20.71%, 47.29% and 32.00% respectively. The percentage composition of both hydrogen and methane increased with a significant decrease in the percentage carbon monoxide. It was however interesting that for R-values above 0.5 it was methane that became the dominant gas where most of the samples were located at the upper end of the triangle indicating the majority of the transformer abnormalities within the Eskom fleet were attributed to thermal degradation failures. This was consistent with the failure statistical findings undertaken within Eskom [Jagers1, Jagers2].

7.2.5. Analysis of Transformers Presently in Service

Figure 7-5 provides a representation of transformer oil samples as recorded in the period 2011 to 2012 for transformers that are presently in service. There were a number of sample points in the abnormal region. These were broken up into the four broad regions A, B, C and D. In region A there were 3 GSU transformers, region B 2 GSU transformers, region C 10 transformers and region D 1 GSU transformer. These are an estimated 16 transformers from a pool of 114 GSU transformers currently in service. From the 16 GSU transformers highlighted 3 transformers in region A and 2 transformers in region C are new and was installed within three years. These transformers are monitored closely with on-line dissolved gas equipment. The remaining 11 GSU transformers are greater than 20 years of age and are currently being closely monitored. Replacement transformers are currently planned for at least 20 GSU transformers over the next 5 years.

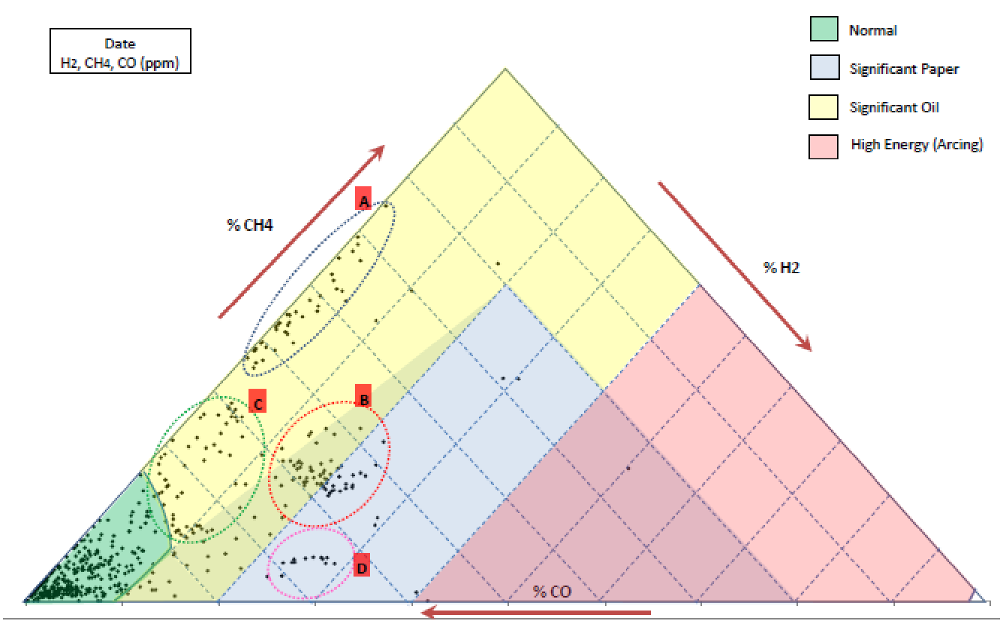


Figure 7-5: Transformers Presently in Service (2011/12)

7.3. FAILURE STATISTICS BASED ON LEDT PREDICTION

Table 7.5 is the statistical analysis of the failed and of transformers that were taken out of service as observed within the LEDT trends. Figure 4-6 can be used as reference for the location of points 1 to 7. From the 201 GSU transformers analysed there were 23 failures. These failures were then analysed in terms of the trend within the LEDT. “All points < 2” means that all points were in the normal region where point 2 is the limit for the normal region. There was one failure experienced in this region. Where there was at least one point in the abnormal region, there was only one failure recorded. It was found that when there was a definite trend from point 1 to 2 there were 4 failures recorded out of the 28 transformers that displayed this characteristic indicating a category rate of failure of 14.29 %. For trends moving straight from point 1 to point 3 there were 22 transformers with 5 failures. The failure rate for this category was 22.73%. When trends moved from point 3 to 4 there was a 33% failure rate.

However, only analysing the failed transformers may be misleading due to at least 87 of the 201 transformers being replaced with new transformers due to the deteriorated condition. When these statistics are added to the failure data it was found that for the trend from 3 to 4 100 % of the transformers were removed. Movement of transformers from points 1 to 7 resulted in 75.76 % of the transformers removed and movement from points 1 to 3 there was 81.82 % of the transformers removed from service.

Table 7.5: Failure Statistics - LEDT

		All Points < 2	1 Point > 2	Few Points > 2	1-2	1-3	1-6	1-7	3-4
Number of Transformers	201	29	28	22	28	22	36	33	3
Number of Failures	23	1	1	1	4	5	7	3	1
Number Replaced	87	6	5	11	11	13	17	22	2
Still In operation	92	22	22	10	13	5	12	8	0
Fail Rate in category		3.45%	3.57%	4.55%	14.29%	22.73%	19.44%	9.09%	33.33%
Fail Rate in category		3.80%			16.39%				
Failed & Replaced		24.14%	21.43%	54.55%	53.57%	81.82%	66.67%	75.76%	100.00%
Failure Rate: 2 > Points > 2		4.35%	95.65%						
Failed & Replaced: 2 > Points > 2		6.36%	93.64%						

When the categories were grouped such that all trends including “all points < 2”, “1 point >2” and “Few points > 2” the failure rate was 3.80% and for trends moving directly from point 1 to point 2, 3, 6, 7 the failure rate was 16.39%.

For the 23 transformers that failed 95.65% of them moved from point 1 (normal) to defective state. It was identified that for the combination of failed and transformers removed from service, 93.64 % of transformers moved from point 1 (normal) to defective state.

7.4. IDENTIFYING THE IMPACT OF GIC

During the investigative process the impact of geomagnetic storms on transformer condition was attempted due to the evidence that GIC induce circulating currents in power transformers giving rise to low energy thermal faults. The proposal that the LEDT was sensitive to the effects of low energy degradation was also tested in this regard.

Gaunt and Coetzee provided evidence of possible GIC damage on at least 12, 700 MVA GSU transformers in South Africa [Gaunt1]. Table 7.6 provides a list of Solar Storms as recorded by the South African National Space Agency in Hermanus for the year 2003.

Table 7.6: Solar Storms Recorded in 2003

Date	Impact	Duration
29/30 May 2003	K-6	9 hours
11/12 July 2003	K-6	6 hours
18 August 2003	K-6	3 hours
21 August 2003	K-6	
14 October 2003	K-6	
24 October 2003	K-6	9 hours
29-31 Oct 2003	> K-6 K-9	21 hours & 24 hours For at least 3 hours in each of the two periods
4 November 2003	K-6	3 hours
6 November 2003	K-6	3 hours
13 November 2003	K-6	3 hours
20/21 November 2003	K-8	15 hours

The following results were obtained when analysis was made on three 700 MVA GSU transformers that were suspected of been affected by GIC storms from 1999 to 2004.

The first example is the GSU transformer as discussed in case study G, as represented in figure 7-6. This GIC analysis was for the same transformer when it failed prior to the installation on the 28 May 2004 as discussed in case study G. Samples are recorded from 21 October 2003. The first set of solar storms recorded were on the 24 October 2003 with a rating of K-6 and lasted for 3 hours, the second was from 29-31 October with a rating of K-6 and K-9 lasting much longer for about 21 and 24 hours respectively. There was a third storm in this period recorded on 4 November 2003 with a rating of K-6 lasting 3 hours. The next oil sample recorded was on the 5 November 2003 which showed upward movement representative of an increase in methane. After this sample there were two significant solar storm activities recorded on 6 November 2003 (K-6, 3 hours) and 13 November 2003 (K-6, 3 hours). The next oil sample recorded on the 20 November 2003 showed a significant step change towards the degradation normal limit boundary. A subsequent solar storm was recorded on the 20/21 November 2003 (K-8, 15 hours) which was a major storm known as the "Halloween Storm." From the oil sample on the 23 November 2003 there was a change in the high energy region where the transformer failed.

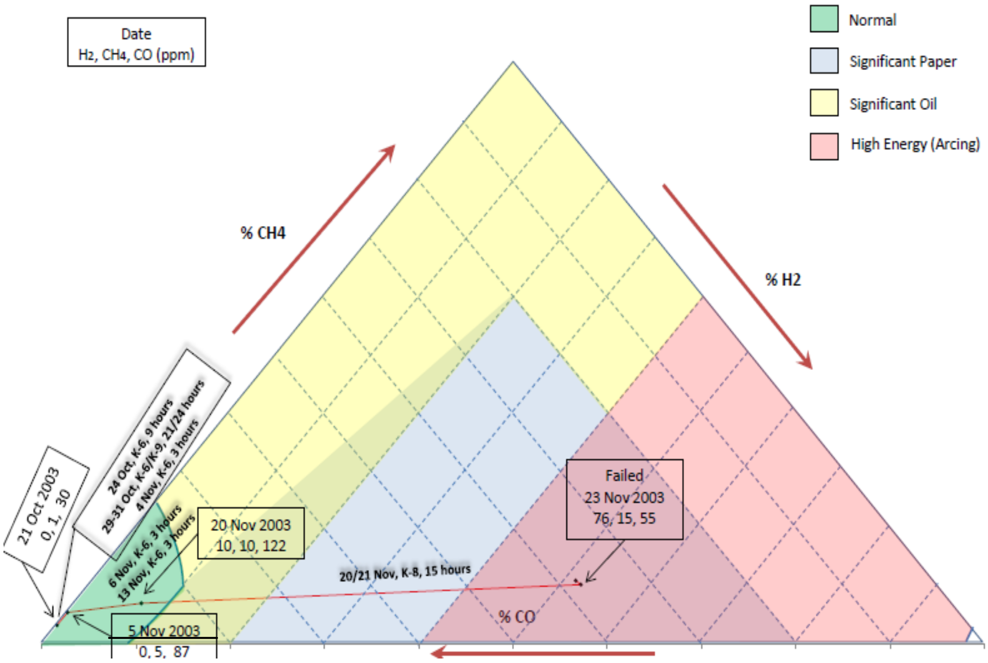


Figure 7-6: LEDT of Case Study G with Geomagnetic Storm Occurrence

The next transformer was initially discussed as case study F where more detailed information can be found for further reference. Figure 7-7 is the updated LEDT to include the record of geomagnetic storm occurrences.

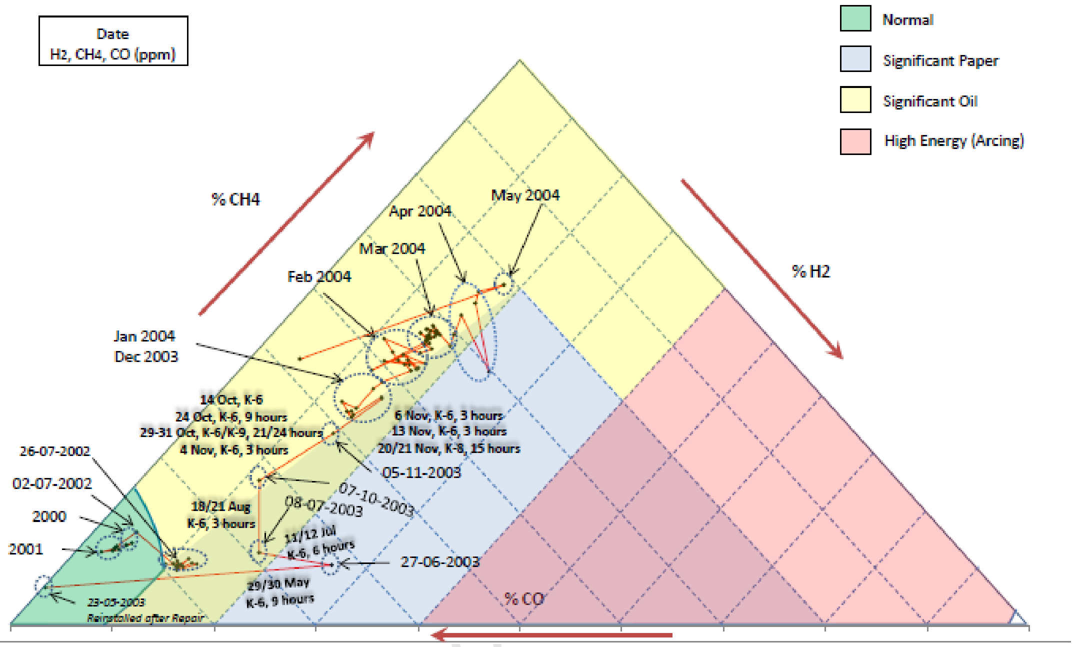


Figure 7-7: LEDT Case F with Geomagnetic Storm Occurrence [Moodley2]

After reinstallation on 23 May 2003, the first solar storm was recorded on the 29/30 May 2003. The next oil sample recorded on the 27 June 2003 was in the defective region. Subsequent samples taken on the 8 July 2003, 7 October 2003 and 5 November 2003 were all preceded by solar storms as recorded in table 7.6. It is found that the solar storm events listed in table 7.6 correlates very closely to the changes in dissolved gases as presented in figure 7-7.

A third case is also recorded for a 700 MVA GSU transformer from the same power station as the above two transformers. The first oil sample was recorded on 10 February 2003. Solar storms were recorded on the 29/30 May 2003 (K-6, 3 hours) where the next two oil samples recorded on the 1 July 2003 indicated a sharp movement into the defective region. The next group of storms were on 11/12 Jul 2003, 19/21 Aug 2003, 24 October 2003, 29-31October and 4 November 2003 as displayed in figure 7-8. The next sample taken subsequent to these storms indicated another step jump in the LEDT. From this date to 19 January 2004 the dissolved gas samples were focused in this area until the transformer was taken out of service.

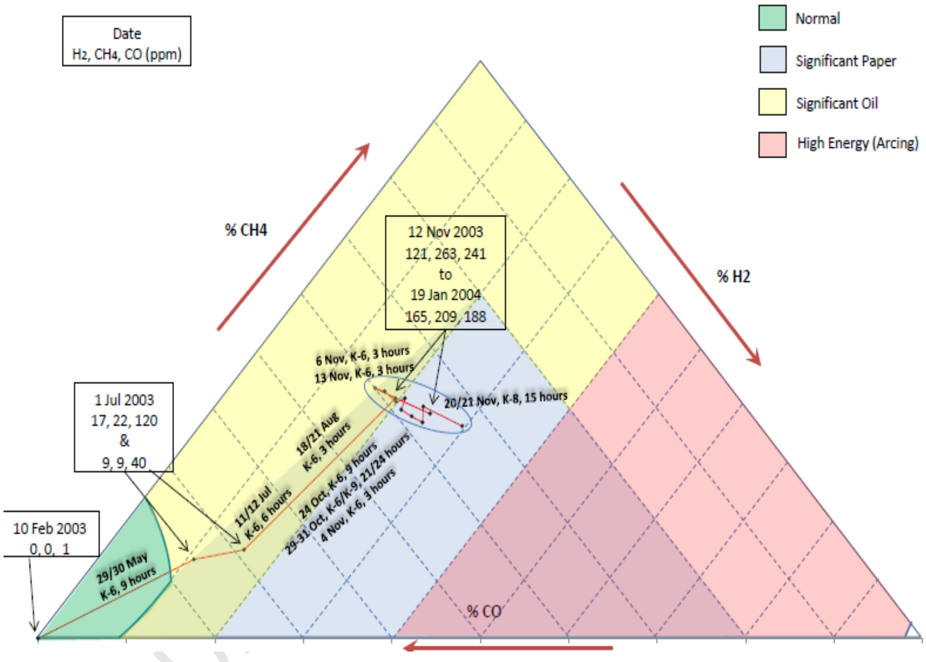


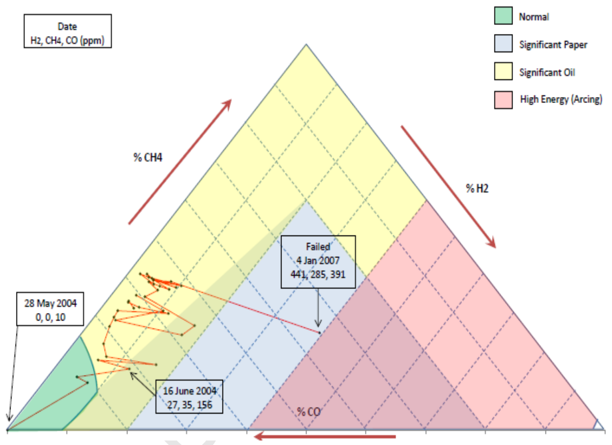
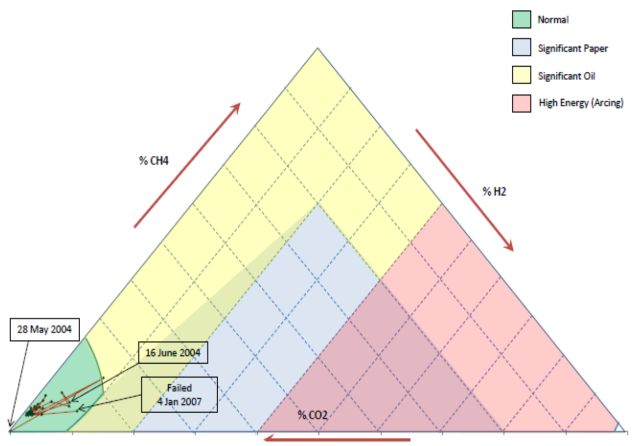
Figure 7-8: LEDT example with Geomagnetic Storm Occurrence

Testing other parameters – CO2, C2H6, C2H4

Figure 7-9 provides a comparison of the LEDT with other combinations using carbon dioxide, ethane and ethylene. It was found that for all the transformers analysed, the plot with carbon dioxide was not sensitive to changes in the dissolved gas results. This was predominantly due to the carbon dioxide values usually being in the order of a few thousand ppm thus diluting the effects of hydrogen and methane.

From the plots with ethylene replacing carbon monoxide it was found that the patterns were erratic and no simple trends were formed.

Ethane provided the closest match to carbon monoxide and hydrogen with samples falling within the regions. There were however no consistent trends of increasing deterioration with the sample points being erratic within the LEDT.

LEDT	**Description**
	<u>H_2, CH_4, CO</u> This LEDT is presented in Case Study F
	<u>H_2, CH_4, CO_2</u> This plot uses hydrogen, methane and tests carbon dioxide in place of carbon monoxide

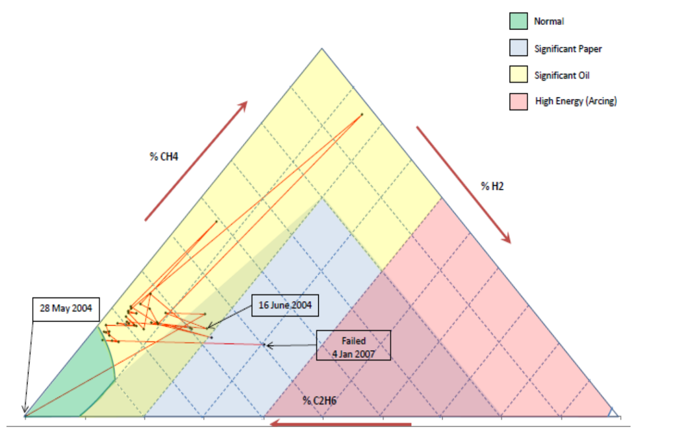
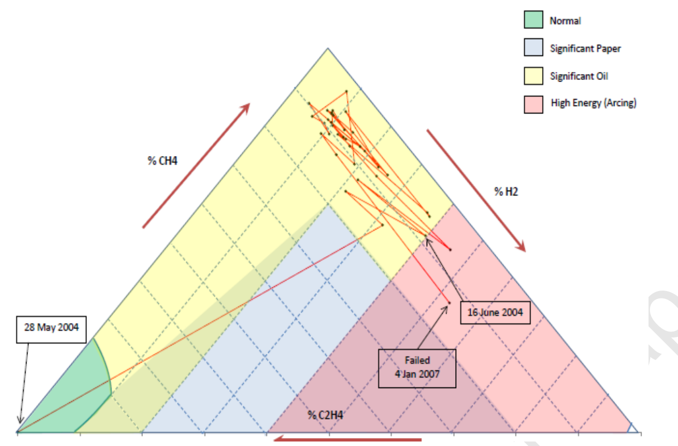
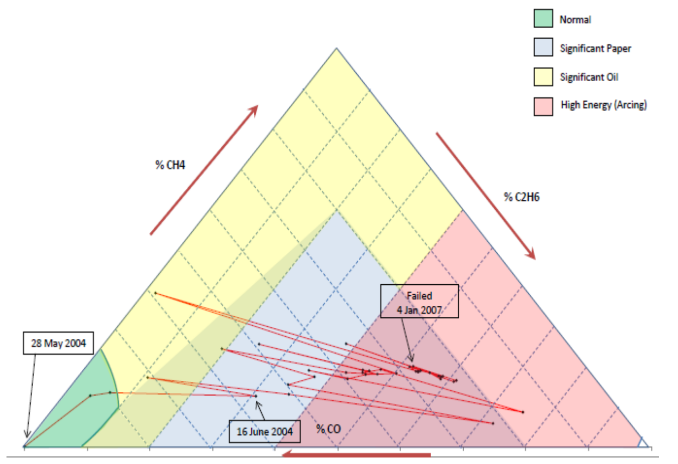
	H_2, CH_4, C_2H_6 This plot uses hydrogen, methane and tests ethane in place of carbon monoxide
	H_2, CH_4, C_2H_4 This plot uses hydrogen, methane and tests ethylene in place of carbon monoxide
	C_2H_6, CH_4, CO This plot uses methane, carbon monoxide and tests ethane in place of hydrogen

Figure 7-9: Comparison of CO_2, C_2H_4, C_2H_6

7.5. HIGH CARBON MONOXIDE LEVELS

This study highlighted the significance of carbon monoxide as an indicator of cellulose insulation degradation. Due to the LEDT being dependent on the three combustible gases hydrogen, methane and carbon monoxide, a high percentage of any one gas will start to dilute the effects of the other two gases. Within a power transformer, this is generally not a major problem but for a few transformers (as in case study I and J) it was identified that the carbon monoxide levels were higher than 600 ppm. This had the effect of raising the trigger value for hydrogen and methane and delaying the defective state trigger.

Thus although the percentage values of hydrogen, methane and carbon monoxide are used in the LEDT, it is important take note of the carbon monoxide values greater than 600 ppm. Another recommendation when assessing transformers with high levels of carbon monoxide was to take note of small step changes in the trend within the normal region as an indication of deteriorating insulation. These must be analysed in conjunction with the actual ppm values of the dissolved gases.

7.6. SUMMARY

Chapter 7 provided a summary of the general analysis of results with respect to the Low Energy Degradation Triangle covering the distribution of dissolved gas samples for R-values within the LEDT. This provided an indication of the limits for hydrogen, methane and carbon monoxide for transformers operating in the normal region. It was also identified that there were significant differences in the average values and distribution of the dissolved gases, especially hydrogen, methane and carbon monoxide as the R-values increased within the LEDT. This distribution was consistent with the theory of the LEDT and boundary limits for normal and defective state.

The oil sample results presented for the period 2011 and 2012 for transformers currently in service provided some indication of the effectiveness of the LEDT in providing a picture of transformers that are operating satisfactorily and those that require closer attention.

From the failure statistical analysis it was identified that movement in the LEDT within the region 3 to 4 (Figure 4-6) for the Eskom GSU transformer fleet 100 % of the transformers have either failed or removed from service. For transformers with dissolved gas samples with movement in the region 1 to 7 it was identified that 75.76 % were removed from service. For movement within the regions 1 to 3 and 1 to 6 there were 66.67 % and 81.82% of the transformers that were removed from service respectively. These statistics may infer a possible link to the probability that transformers depicting similar profiles are likely to have the same percentage probability of being taken out of service whether planned or due to a failure.

The three GSU transformer cases presented with regards to the influence of GIC on the dissolved gas composition provided high correlation between the geomagnetic storm occurrences to that of the movement within the LEDT indicating insulation degradation. This analysis does provide some confidence that there may be a link between the effects of GIC and dissolved gas production.

As a diligence check an intense analysis was conducted on the database of dissolved gas samples to identify if any of the other combustible gases can provide more meaningful trends within the ambit of testing the hypothesis of this study. From the results summarised in this chapter it was still identified that the three combustible gases hydrogen, methane and carbon monoxide provided the most consistent and reliable insulation degradation parameters to assess transformer health under low energy degradation mechanisms.

A limitation identified in this study was that high carbon monoxide values, usually above 600 ppm tends to delay the defective state trigger within the LEDT.

CHAPTER 8

CONCLUSION

This thesis started with critical questions on how to assess the health of a power transformer and how to identify a defective state as soon as the insulation degradation process has started. This early warning is crucial in determining the course of action applied by transformer engineers to maintain the designed life of the transformer. The conclusions made in this chapter provide significant advancements in achieving the answers to these questions.

8.1. CONCLUSIONS

Important aspects identified in chapter 2 was that GSU transformers due to the high loading had a high number of failures related to the internal of the transformer such as windings, core, leads and tank. Literature research on failure mechanisms had highlighted that the main life limiting components that determine the health of the transformer are the cellulose and oil based insulation.

Chapter 3 provided the building blocks for the study identifying that the paper and oil insulation degrades at varying rates, which is dependent on the degradation mechanisms such as elevated operating temperatures, pyrolysis, partial discharge, corona, arcing, hydrolysis and oxidation. The severity lifespan model provided an approach to assess transformer health risks and how these risks developed over time.

One of the inherent catalysts of insulation degradation is energy. Energy focused on especially areas with insulation material for long periods facilitates degradation processes that may be of chemical, thermal or electrical in nature. The normal losses in the transformer are designed within the capabilities of the transformer insulation to achieve its design life. However defects in design, manufacturing, operating and maintenance can create opportunities for defective levels of energy to be retained within the transformer. The energy concept in chapter three provided a detailed investigation into these sources and the impact on insulation. It was found that high energy sources such as arcing and severe thermal heating are the most destructive to paper and oil insulation forming rapid levels of dissolved gases such as hydrogen, ethylene and acetylene. For low energy sources, the prominent dissolved gases are hydrogen, methane and carbon monoxide.

The fundamental aspect of this study was that thermal and electrical degradation of the transformer insulation systems produced dissolved gases. From the typical combustible gases monitored, this study focused on hydrogen, methane and carbon monoxide due to these gases being prevalent in low concentrations even for no fault conditions. The methods identified in this model are most effective when there is no detection of acetylene and very low levels of ethylene. Both of these combustible gases are associated with high energy conditions. It is felt that when there are trace elements of acetylene and significant levels of ethylene, a fault condition already exists which has progressed to a stage where conventional analysis methods can be applied for more accurate diagnosis and management.

It was found from the general analysis of results and case studies that the LEDT offered a potentially significant advantage in identifying trends of insulation degradation. In most instances triggers were received within a few years before the failure occurred. The LEDT method is however potentially effective when applied to on-line monitoring systems. The important aspect of the LEDT is the trends. The LEDT is effective enough to provide a single sample analysis and degradation progression with trending. It is highlighted that the LEDT has currently only been tested on the GSU transformers within the Eskom fleet and relevance to other utility transformers must still be tested.

8.2. ANSWERING THE RESEARCH QUESTIONS

The following research questions need to be answered to test the validity of the hypothesis:

What are the shortcomings of the existing incipient faults identification methods?

From the literature survey and experience it was found that there was still a high dependence on expert knowledge for the interpretation of the different fault identification methods. This poses a challenge as incipient faults go unnoticed until it is in the advanced stages.

Some incipient fault identification methods are not consistent in identifying incipient faults and often misdiagnose defective conditions in other transformers.

Dissolved gas trends are usually erratic and there is often no definite trend. It was found from this study that even with cyclical increases and decreases in the dissolved gas trends the corresponding LEDT still provided meaningful trends for assessing insulation degradation and incipient faults.

The analysis of this study has shown that in some transformers, even though the dissolved gases were within the normal limits the LEDT displayed a true defective state trigger. This is another deficiency of the existing fault identification methods as low dissolved gas levels are automatically interpreted as normal.

The current fault identification methods are not effective in providing a trend from normal to defective state.

How does the energy inside the transformer change for normal and fault conditions?

Power transformers may be seen simplistically as an energy transfer device by varying the voltage and current. The efficiency is usually high so under normal operating conditions the The energy due to losses are transferred from the windings and core to the oil and then from the external cooling dissipated to the surrounding environment.

When there are any defects in this energy transfer process, this energy is retained in localised areas. Blockages in cooling ducts impede the flow of oil and in those regions effective energy transfer does not take place. The localised build up of energy dissipates into the insulation and usually starts to degrade the paper insulation or oil.

Most energy related faults in power transformers start off in localised areas and are not serious enough to significantly affect the top oil temperature. Under electrical fault conditions the energy released is usually high as the current flow from the main circuit was dissipated within the transformer. This usually results in the rapid degradation of the insulation and metal components. Partial discharges and corona are however considered to be low energy electrical activity.

What mechanisms are required for the decomposition of oil and paper? How do these mechanisms affect transformer health?

The severity lifespan model provided a method to identify the different transformer degradation mechanisms with related impact to the transformer life in the long, medium and short term.

Oil degrades under high levels of moisture, oxygen and temperature. Hydrolysis have been noted as a destructive process causing oil to break down under chemical reaction with water. Elevated levels of oxygen result in the oxidation of both oil and paper insulation. The oxidation process produces acids, which becomes a catalyst to sustain both hydrolysis and oxidation which then becomes a self sustaining process.
Pyrolysis is the chemical decomposition of organic material like oil and cellulose under elevated temperatures without the presence of oxygen. This has the effect of producing hydrogen and methane with some carbon under severe conditions.

The effects of corrosive sulphur have been noted as a process that has significantly affected the transformer health over recent years. There are two prevalent failure mechanisms which are attributed to either reducing the dielectric properties of the paper insulation or creating a conductive path. This process is affected by elevated temperatures and usually do not release dissolved gases.

Other insulation degradation mechanisms include partial discharge and corona, arcing and system conditions like over voltages. Partial discharge is prevalent in electrical equipment with insulating material and usually under voltage gradients. This is a slow process but can be destructive leading to the more severe form of arcing. These mechanisms are electrical in nature and the level of energy may start off low but reaches extreme levels under arcing conditions.

What are low energy degradation mechanisms and how can these be identified?

Low energy mechanisms are hydrolysis, oxidation, pyrolysis, partial discharge and the effects due to thermal heating. It was challenging to identify a clear measure of the rate of hydrolysis, oxidation and pyrolysis due to the dynamic nature of oil, loading and environmental conditions. The level of degradation of these mechanisms is usually identified indirectly. The moisture and acidity levels provide some indication of the rate of these conditions. Usually the production of sludge is a reliable indication of the advancement of these processes.

Partial discharge, especially with the involvement of oil, is identified with the elevated levels of hydrogen and low levels of the other typical combustible gases. Thermal faults of low energy involving oil usually produce methane and ethane with some ethylene. Where cellulose was involved the levels of carbon monoxide increased under thermal conditions.

What factors affect dissolved gas trends?

From experience and the analysis of this study it was found that the most significant cause of ineffective dissolved gas trending was the reliability of oil sample data [Duval4]. Sample conditions like oil temperature, method of sampling, exposure to the environment, packaging, storage, transporting and the analysis of the oil samples plays an important role in achieving consistent reliable dissolved gas data [Tenbohlen1].

From this study it was found that the filtering or processing of the oil had a significant effect on the levels of dissolved gases. On most occasions this had provided a false sense of security where there was a significant decrease in the combustible gases but within the next two samples the elevated levels were once again present. It was thus very important for clear records to be provided on the exact date of when the oil was reconditioned or replaced and these must be taken into account when analysing dissolved gas trends.

The loading of the transformer also plays a significant role in affecting the dissolved gas trends. This was particularly noted for transformers which were operated intermittently for hydro power stations. Any fault condition present does not have a long enough loading time to produce elevated combustible gas levels beyond the normal limits or ratios.

How do dissolved gases react under different energy conditions?

From the literature and analysis of this study it was identified that for low energy faults the prevalent dissolved gases were hydrogen, methane and carbon monoxide. Methane production was primarily from the degradation of oil and carbon monoxide from the degradation of cellulose insulation.

Medium energy conditions up to temperatures of 700 °C produced ethane and ethylene with hydrogen, methane and carbon monoxide. The levels of methane and carbon monoxide started to decrease towards the higher end of the temperature.

High energy conditions like arcing result in the rapid production of acetylene and hydrogen. Thermal faults of high energy have significant concentrations of ethylene. The gas production rate increases at elevated fault energy levels.

How does Geomagnetic Induced Currents affect the energy changes within the transformer? Can the effects of GIC be identified?

Geomagnetic induced currents have the effect of driving the transformer into half cycle saturation with the saturated core limbs causing most of the excess flux to flow through adjacent paths. This may set up eddy currents with localised hotspots on the tank, clamps and windings.

From the conventional fault identification methods, there has been little support in identifying the effects of GIC. From the analysis of this study the LEDT did provide meaningful trends for transformers that were suspected of experiencing some effects from GIC. The correlation of the GIC storms to the movement in the LEDT on at least three GSU transformers had been high indicating that the effects of GIC on GSU transformers could be identified.

8.3. ASSESSING THE HYPOTHESIS

The hypothesis tested in this study is *can low energy changes within a power transformer affect the composition of dissolved parameters in such a way that allows the effective identification of insulation degradation and incipient faults.*

This study systematically investigated the various aspects of this hypothesis. The first part of the analysis was to identify the sources of low energy within the power transformer. The second part identified components in the transformer that are most affected by the dissipation of this energy. The third part investigated how these components are affected and the most effective way of detecting the effects of this energy dissipation. A low energy model was then formulated to test this hypothesis on real data as collected on GSU transformers within the Eskom Power Utility.

The research questions provided the necessary direction for a methodology to test the hypothesis. Some of the low energy sources like partial discharges, thermal faults such as inadequate cooling and circulating currents are usually the start of the insulation degradation process. These processes affect the paper and oil insulation in the transformer, which are usually the components that limit the life of a power transformer.

Numerous methods for the condition monitoring of a power transformer are available but the most effective in assessing insulation degradation are dissolved parameters from oil samples. It was found that not all dissolved parameters are directly related to the effects of energy dissipation with the power transformer. The most notable in this regard was the combustible gases hydrogen, methane, ethane, ethylene, acetylene and carbon monoxide. From these combustible gases, this study identified hydrogen, methane and carbon monoxide as being the most effective in capturing the possible effects of low energy degradation.

The formulation of the Low Energy Degradation Triangle (LEDT) provided a relationship among the three gases hydrogen, methane and carbon monoxide as a model to test the hypothesis. The 12 case studies presented in this study provided an opportunity to take a retrospective approach in analysing the capabilities of the Low Energy Degradation Triangle. These case studies provided invaluable information by effectively confirming transformers operating normally and changes to the defective state that have resulted in either a failure or removal of the transformer from service. The LEDT was most effective in providing a visual trend of the deteriorating state of the transformer insulation. This was confirmed with the visual inspections of transformers that were taken out of service. When the defective state trigger was received, it has been usually well in advance of the final failure event.

The LEDT also provided true defective state triggers even when the dissolved gas samples were well within the normally accepted limits. This supported the notion that paper and oil degradation at low energy (temperatures) does produce dissolved gases in relation to the level of thermal degradation experienced.

The R-value derived from the polar representation of the sample points within the LEDT had provided an effective measure of the level of degradation. This was confirmed with the R-value trends for the case studies where there were definite increasing trends leading up to failure. The R-value normal limit of 0.173 provided an effective boundary for the trigger of normal state to that of defective, which may also be representative of the development of incipient faults.

Majority of case studies presented started off with low dissolved gas levels and with the transformers falling in to the normal region of the LEDT. Progression of the dissolved gases to higher levels have resulted in the movement to the abnormal state where failures occurred. It was found that most of the evidence presented as a result of winding damage which was inspected only after failure are of the high energy. However due to this very reason the incipient fault region was always “damaged”. A possible consideration was that if these failures started of from high energy mechanisms the failures on some of the transformers would have been much quicker. The fault progression process on some of these transformer took a few years until final failure suggesting slow fault degradation of the insulation. The application of the LEDT on transformers suspected of being affected by geomagnetic induced currents (usually low energy mechanism) were also tested and there was good correlation between the solar storm events and the dissolved gas levels further supporting the hypothesis that low energy changes within the transformer does affect the composition of dissolved gases. These cases does provide some validation of the LEDT being able to detect the influence of of low energy degradation mechanism.

From the literature research and analytical analysis of dissolved gas data of 201 GSU transformers within the Eskom power utility, there was significant evidence to support the hypothesis that low energy changes within a power transformer do affect the composition of dissolved parameters in such a way to allow the effective identification of insulation degradation and incipient faults.

8.4. LIMITATIONS

One of the limitations identified was that for transformers with high levels of carbon monoxide greater than 600 ppm, there was a tendency of a delay in the defective state trigger. The LEDT method would thus potentially be more relevant to open breathing transformers due to it generally being a characteristic for closed transformers to exhibit high levels of carbon monoxide without any fault conditions. A possible mitigation for this is the observation of the small trends within the normal region and the assessment of the actual ppm values for hydrogen and methane.

It is noted that the findings of this study with regard to the LEDT method is relevant to the data as tested for the Eskom GSU transformer fleet. Relevance to other utility transformers must still be tested.

8.5. CONTRIBUTIONS

From this research study the following are highlighted as being the main contributions to the body of knowledge and industry.

8.5.1. Primary Health Assessment Tool

One of the key contributions of this method is that it is not developed to replace the existing fundamental fault diagnosis methods but to rather detect a change of state from that of normal ageing to that when there is a defective state starting to form. The novel aspect of the LEDT model is the combination of the three key gases (hydrogen, methane and carbon monoxide) in a triangular representation to provide a clear normal operating region. The LEDT also provides some confidence in being able to possibly detect the insulation degradation effects of geomagnetic induced currents as caused by solar storms.

8.5.2. Eskom

This study by its nature analysed the entire fleet of GSU transformers for the Power Utility Eskom. Of these 114 GSU transformers still in service, defective state triggers were found for 16 GSU transformers. These transformers have been highlighted within the organisation as being risky and should have closer monitoring.

Out of these 16 GSU transformers there were 6 transformers highlighted as being critical. The relevant asset management has been notified of these risks and replacement strategies have been put in place for these transformers over the next 2-5 years.

8.6. FUTURE WORK

Within Eskom, the LEDT model must be applied on a wider scale to other transformers within the Transmission and Distribution groups. Interesting aspects such as the loading profiles of the transformers, ageing and exposure to switching surges must be tested due to exposure of these factors in the transmission and distribution environment.

With a larger database (worldwide) of failed transformers it is the author's belief that the LEDT can provide valuable information on the type of fault developing. This allows room for further research and collaboration within the industry and research fraternity.

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