Condition Assessment Using Dissolved Gas Analysis on Transmission Power Transformers

University of Cape Town

MSc (Eng) Thesis

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Declaration

I declare that the work done in this dissertation is my own, save for the properly acknowledged work from other researchers used in the research and referenced accordingly.

Signed by candidate

02/07/2024

Abstract

In transmission networks, power transformers and reactors play a major role in the supply of power in the country. Power transformers and reactors are identified as most critical assets and have a significant impact on power network reliability. It is thus important to know the effective condition of the transformers and reactors to reduce the risks of unplanned outages as well as catastrophic failures.

The objective of this research is to evaluate the effectiveness of the Low Energy Degradation Triangle (LEDT) technique for the early detection of incipient faults evolving in transmission power transformers and reactors. Further evaluation is made using other generally accepted DGA diagnosis methods such as Roger’s Ratios, Doernenburg’s Ratio, Duval’s Triangle 1, Duval’s Pentagon 1 and a proposed Medium Energy Degradation Triangle (MEDT).

All these techniques were evaluated by collecting data from previous failures from transmission transformers. Historical data collected were taken from the first available oil samples up until the transformer showed ageing or failure. The results from this study were compared with experimental results performed from publications.

Eskom transformers and reactors utilise mainly mineral oil insulation and there is an intent to use non-mineral oil as well in the future. This research also focused briefly on the evaluation and diagnosis of incipient fault development in ester oil-filled transformers and reactors.

The LEDT provided mostly reliable results for detecting incipient faults in transmission and GSU transformers and allowing the plant to engineer enough time to plan the required outage.

This study has identified that both the LEDT and Duval’s Triangle 1 provide useful but different interpretations for the assessment of transformers filled with natural and synthetic esters. However, further investigation is required due to the current low experience of power transformers filled with these oils.

Acknowledgements

First of all, I would like to thank Professor CT Gaunt of the Faculty of Engineering and the Built Environment and the Electrical Engineering Department at University of Cape Town for allowing me to present my work to complete my thesis under his intelligent wisdom. His consistent guidance and encouragement gave me the strength to finalise my research.

Furthermore, I appreciate my industrial supervisor Dr N Moodley for his time patiently guiding and assisting me from the darkest path and leading me to see a light on my way forward.

Special thanks to my two wives and my beautiful children for allowing me to take their time and their support to fulfil my dream goal at my age.

I will not forget Sidwell Mtetwa as my colleague for his support, undertaken by him during the investigation on transmission substation.

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Gases

H_2	Hydrogen
CH_4	Methane
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CO	Carbon monoxide
CO_2	Carbon dioxide
O_2	Oxygen
N_2	Nitrogen

Areas within diagnostic diagrams

T1	Thermal Fault t≤300℃
T2	Thermal Fault 300℃ ≤ t ≤ 300℃
T3	Thermal Fault t≥700℃
D1	Discharge of Low Energy
D2	Discharged of High Energy
PD	Partial Discharged
T1	Thermal Fault t≤300℃
DT	Transition of type of fault

Abbreviations

DGA	Dissolved Gas Analysis
GSU	Generator Step Up
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LEDT	Low Energy Degradation Triangle
MEDT	Medium Energy Degradation Triangle
MVA	Mega Volt Ampere
ND	No Diagnosis

1 Chapter 1: The state of transformer gas-in-oil diagnosis

A power transformer is a static piece of equipment that requires minimal intrusive intervention during its lifetime due to the nature of its construction and use. Large transformers are manufactured in a special environment and mostly cannot have major repairs on-site. There have been cases where transformers were removed from service for preventative maintenance and immediately after the maintenance, they either failed or were defective. All these issues eventually translate to an asset failure, shorter life span, inability to perform to the expected output, or combinations of these. The outcome is often costly to the transformer supplier if the unit is still under guarantee and to the utility in terms of risk elimination and the interest during construction on a delayed project. In response to this problem, techniques have been developed to identify potential major failures in their infancy stages by dissolved gas analysis and rectify them at minimal costs, or to identify and assess the implications.

1.1 Condition monitoring

A transformer’s oil and solid insulation systems have an important role as a dielectric medium protecting against flashover to conductive parts and as transport of thermal energy dissipated in the core and winding to the external cooling. Mineral oil has been a preferred liquid insulation in liquid immersed transformers for its dielectric strength and cooling capability. However, the solid paper insulation is the main contributing factor to transformer life expectancy and degradation that should be monitored to identify risks to maintaining the transformer in a healthy condition.

1.1.1 What can cause a transformer to fail?

The flow chart in Figure 1-1. shows the possible causes of the transformers/reactor’s failure from transmission and distribution network. The data was gathered from literature research, case study investigations and from IEC/IEEE guidelines [IEC 60599]. These causes can contribute to different types of faults in the oil-filled transformers/reactors such as thermal and electrical faults. Furthermore, these processes generate dissolved gases that can reduce or reflect reduction of the dielectric strength of the insulation. This figure can assist in identifying the root cause of failures.

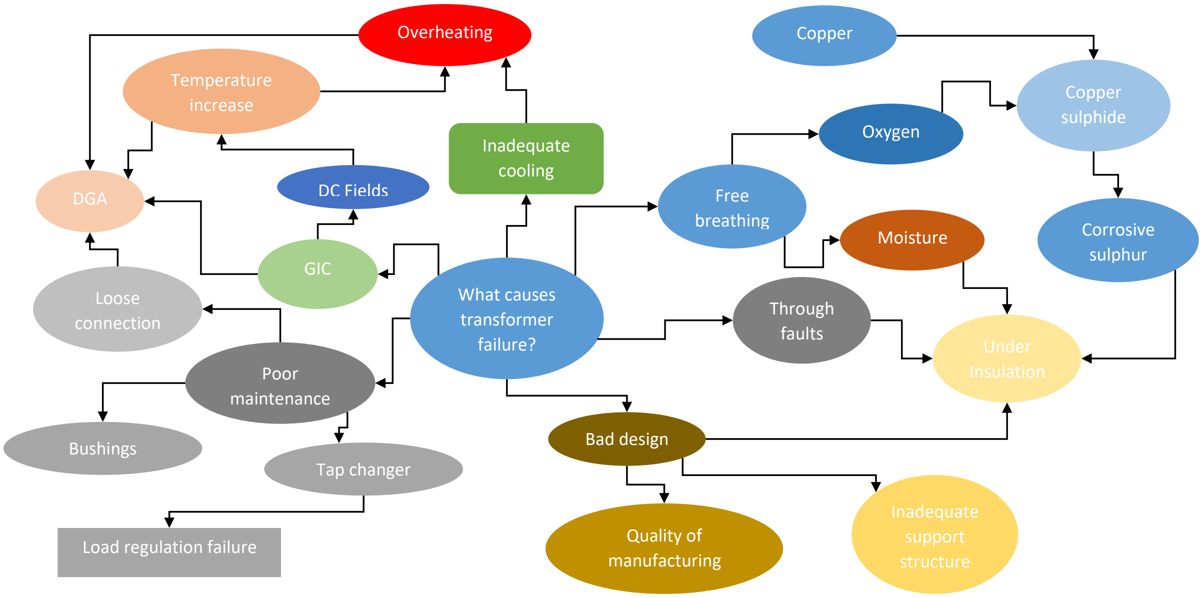


Figure 1-1: Causes of failures.

The key elements that need close attention in the transformer are electrical, mechanical, and thermal faults. The mechanical problems cause the solid insulation to collapse, and the electrical problems start electrical discharges because of clearance compromised. Mostly, thermal problems are caused by loose components or high resistance which cause overheating in the transformer. The core and windings can also overheat because of over fluxing and over loading. All these mentioned problems produce dissolved gasses which affect the dielectric strength of oil insulation.

International guidelines from IEC and IEEE describe the methods and interpretation of Dissolved Gas Analysis (DGA), which is used by utilities around the world to monitor the condition of the transformer insulation and detect incipient faults before they become catastrophic to the equipment [IEC 60599] [C57.155-2014]. However, to analyse the results of the gas measurements correctly, sound engineering judgement is required, usually guided by generally accepted parameter analysis methods such as Duval's

Triangle 1 and Roger' Ratios [Duval 2002] [Huo-Ching 2012]. Other methods that evaluate the ageing process relate to the deteriorating condition of cellulose material include the degree of polymerization measurement and Furan analysis. Despite these methods, when degradation or an incipient fault is identified, it is still difficult to ascertain whether a transformer needs to be taken out of service or can continue in operation.

Most existing assessment methods appear to be directed at identifying the type of degradation, without identifying trends towards failure or the remaining life of a transformer. Relatively recently, the Low Energy Degradation Triangle (LEDT) assessment approach was proposed [Moodley 2017] specifically for identifying trends towards failure that can provide information to guide decisions for removal or continued operation. The LEDT identifies an early change in state from a normal to an abnormal condition giving an engineer time to plan appropriate action.

During the past 20 years, there have been moves towards using alternative liquid insulation. Ester oils have higher viscosity, higher flash point and are environmentally more friendly than conventional mineral oils. The monitoring of transformers filled with ester oil could use the same existing approaches, however, the ester oil properties are slightly different from those of mineral oil and the assessment criteria must be adjusted accordingly.

Continuity of operation is important for customers, and also for power utilities to ensure the integrity of the power grid. If a transformer fault causes unplanned outages, there is not only a risk of a major loss of the utility's asset, but the utility could lose revenue because of interruptions of supply to customers. Hence, it is important to formulate a procedure detailing when a damaged unit is removed from service and can be returned to service.

The generator step-up unit (GSU) transformers in power stations generally cause loss of the generation capacity when removed from service, because a generator is connected to only one transformer. By contrast, transmission transformers usually have n-1 redundancy, with transformers normally operating in parallel and sharing the load, but able to carry the whole load if one transformer is not available. This makes it easier to take one transmission system transformer out of service for repairs or to investigate a condition that may be an incipient fault, compared with a GSU transformer. Also, because transmission transformers usually operate with loads much lower than their rated capacity, the degradation processes may not be the same as in GSU transformers, on which the LEDT development was mostly based.

1.2 Hypothesis to be investigated.

Even from the short introduction, there appear to be several “unknowns” in the degradation and failure of transmission transformers and the interpretation of gas results. This research intends to investigate existing methods for interpreting DGA gases in mineral oil in transmission transformers, especially assessing how well incipient faults can be detected during the early stages of fault development. A further aim of the study could be to assess to what extent the existing methodologies for DGA interpretation can be used for transformers filled with natural ester oil.

New contemporary methods are used in conjunction with existing methods to provide complete/comprehensive information of faults as well as indicate the condition of a transformer. A proposed solution should provide relatively comprehensive information on the status of the transformer condition by combining the results of existing solutions.

In Eskom Generation, the LEDT method was successfully applied to the GSU transformers to monitor the degradation of the insulation [Moodley 2017]. In this study, the LEDT method is tested on transmission transformers.

The approach to the analysis will be to investigate case studies of failed transmission transformers by analysing DGA and failure data. Ester oils will also be reviewed to identify early degradation processes, shortened life and (perhaps) indications of failure trends. The validation will be based on data from the Eskom laboratory and transmission transformer failure reports.

The LEDT technique has been used to identify the incipient faults in the GSU transformers. There is a possibility that the approach underlying the successful application of the LEDT to degradation identification in GSU transformers can be adapted to improve the analysis of DGA data from transmission transformers and extended to the degradation of transformers with ester oils despite their different properties from mineral oils.

Therefore, the starting point for the research is to propose the following hypothesis that will be investigated in this study:

The LEDT method can identify early detection of insulation degradation and incipient faults in transmission transformers for transformers filled with mineral oil and with ester oil.

1.3 Research questions

The research questions needed to test the validity of the above hypothesis include:

- What are the properties of the key dissolved gases that make the combination of their measurements meaningful for condition monitoring?
- Is the LEDT method and other methods such as Duval's Triangle 1, Rogers Ratio and Doernenburg effective in interpreting the dissolved gas results for transmission transformers filled with mineral oil?
- Can more than one of the above methods be combined to predict the condition of the transformer accurately?
- To what extent can these methods developed for mineral oils be used to assess the condition of a transformer filled with ester oils?

1.4 Research Methodology

The focus of this research is to investigate the existing methods for interpreting dissolved gas analysis results from mineral and esters insulation fluids. The approach taken will be based on an extensive literature review and testing the revealed ideas in the context of case studies of failed transmission transformers using data and records from the Eskom Laboratories. The approaches applied to the interpretation of results from mineral oils will be extended to ester oils on the basis of what the literature review provides. Various methods of interpreting DGA results will be compared with each other. The approach to the research is illustrated in Figure 1-2.

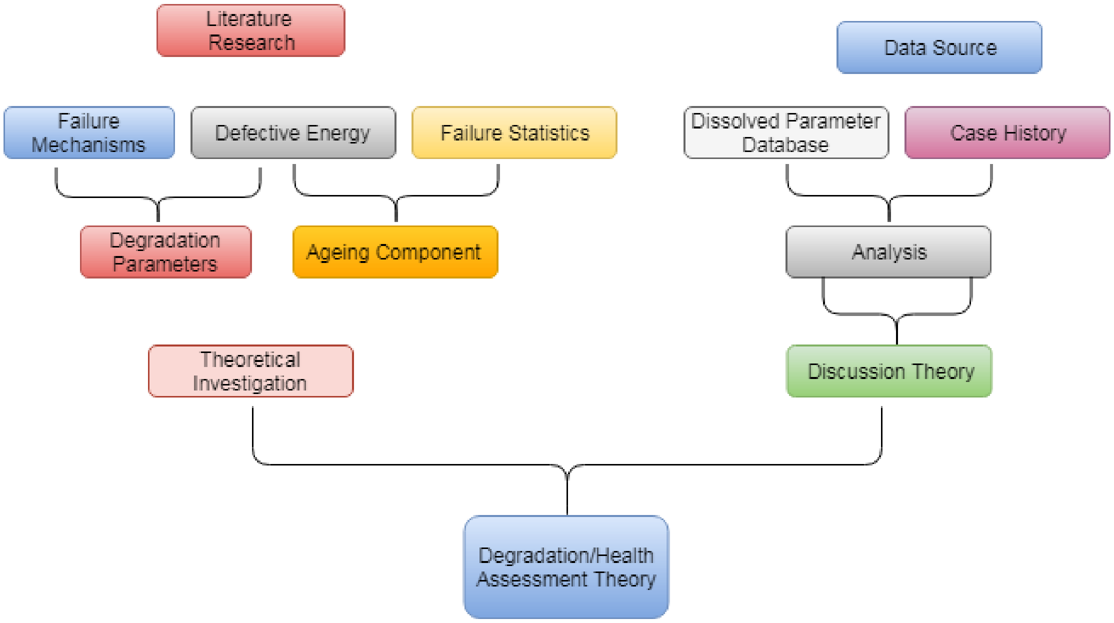


Figure 1-2: Research methodology flow chart

1.5 Structure of the report

This chapter introduces an investigation of the interpretation of dissolved gas analysis (DGA) results from oil-immersed transformers. A hypothesis is identified as the focus of the research, with research questions to guide the investigation.

Chapter 2 reviews the existing literature on conventional methods of interpretation and for useful data. Diagnosing the type of fault or developing degradation from the chemical decomposition of the insulation will be studied for mineral and ester oils. If possible, any gaps in the existing knowledge and approaches will be identified.

Chapter 3 provides a description and development of the LEDT method of trend identification with R-values, and an extension to medium energy degradation.

Chapter 4 examines the case studies of transformers and reactors that were de-energised or failed in the Eskom network. It includes comparisons of the interpretations made by different methods.

Chapter 5 discusses the findings from the case studies with the objective of identifying the most suitable interpretation methods.

Chapter 6 extends the interpretation of mineral oil filled transformers to similar methods for ester filled transformers.

Chapter 7 reviews the various findings of this study, draws conclusions and offers some recommendations.

2 Chapter 2: literature review

This chapter examines the literature on existing methods of interpreting DGA results. It reviews previous studies done by other researchers and adds any general knowledge pertinent to the topics. Where possible, answers to the research questions posed in section 1.3 will be identified. The broad objective is to enable an incipient fault to be identified at an early stage, to give asset managers opportunities to plan outages.

2.1 Insulation

There are different types of insulations in transformers and reactors. The common insulating liquids are mineral or ester oil for oil-immersed equipment. Paper (cellulose) insulation is commonly used for insulating the live conductors.

Moisture significantly reduces the insulation strength and effective lifetime of both solid insulation and fluid insulation [Liao 2011]. It is well known that excessive water in the insulation materials is detrimental to a transformer. The moisture that exceeds the specified limits in the liquid insulation can cause low dielectric strength and in cellulose can accelerate ageing that can lead to early failure of a transformer.

The liquid insulation is the key component for insulating the active part of the transformer and for transferring heat out of the windings. Mineral fluids have been approved as an adequate insulator for electrical apparatus for decades. They have good dielectric strength to withstand electrical stresses imposed in service as well as a combination of thermal conductivity, specific heat, and viscosity to provide good heat transfer in the active part of the transformer [Mehta 2016]. It is compatible with other insulating materials used, especially paper and pressboard, and does not deteriorate in ways that affect other materials used in the transformer. Although the use of mineral oils in power transformers has proven to be reliable it also has disadvantages in its ageing, risk of fire when faults occur, and the environmental endangerment resulting from a transformer spillage [Borsi 2008]

2.2 Insulation degradation

At high temperatures and high electrical stress, both paper and oil insulation decompose into other chemicals, including several characteristic gases, according to the different materials [Fofana 2002]. The chemical bond of the insulating materials breaks down when energy is released in the operating transformer [Xiang 2016]. Gases are the product of oxidation and vaporisation of insulation decomposition and oil break down in a transformer. The gases dissolve in the oil. The breakdown process of carbon-carbon and hydrogen-carbon bonds in oil and paper result in a complex mixture of hydrocarbon gases. The concentrations of the gases depend on the temperature of the localized reaction [Muradov 2001] [Susilo 2013]. The gas composition is dynamic with generated gases being absorbed, changed chemically, or evaporated. Also, moisture in solid insulation migrates into the oil and starts the degradation process of the dielectric strength in oil.

The following generally accepted key gases are widely measured to provide some information about degradation and faults [Hamrick 2010].

The combustible or hydrocarbon gases are:

- Hydrogen (H_2)
- Methane (CH_4)
- Acetylene (C_2H_2)
- Ethylene (C_2H_4)
- Ethane (C_2H_6)

and the non-combustible gases are:

- Carbon monoxide (CO)
- Carbon dioxide (CO_2)
- Oxygen (O_2)
- Nitrogen (N_2)

Figure 2-1 displays dissolved gases generated by the degradation of the insulation system in an oil-filled power transformer according to thermal or electrical stress [Mhrakurwa 2019] [Arakelian 2002]. Some researchers separate the electrical stress into different categories: partial discharge and dielectric arcing [DiGiorgio 2005].

There are many techniques available to interpret the fault gases, however, in most cases, they produced different results without consistency [Chang 1967]. Intelligent fault diagnosis techniques manage to interpret the fault types generated; however, early-stage fault progression from normal to abnormal state was not evident [Pople 1982].

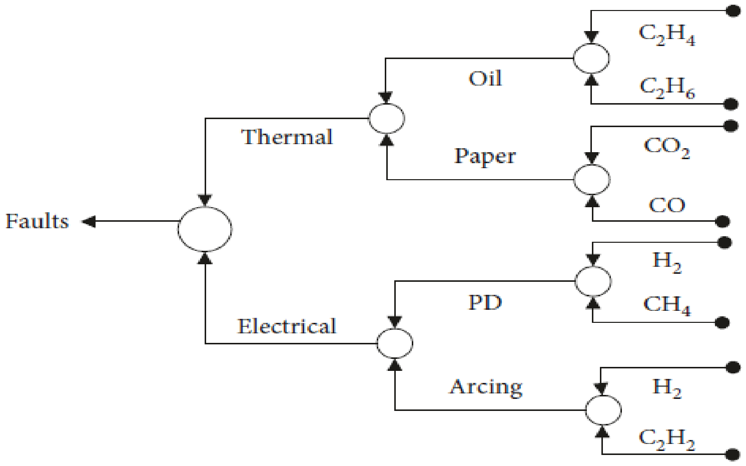


Figure 2-1: Fault generated gases [Mharakurwa, et al., 2019]

When the cellulose of solid insulation starts degrading from thermal decomposition or electrical faults it produces hydrogen (H_2), methane (CH_4), carbon monoxide (CO) and carbon dioxide (CO_2) [Hamrick 2010]. These fault gases are generated at relatively low temperatures.

Mineral oils used for transformer insulation are mixtures of various hydrocarbon molecules where the breakdown process of the molecule bonds is known as gassing oil [Hamrick 2010]. During the hydrocarbon breakdown process, the atoms form fault gases methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6) and acetylene (C_2H_2) at increasing temperatures, and hydrogen (H_2) in electrical discharges. These are illustrated in Figure 2-2.

The most recognised method utilised worldwide for detecting incipient faults in the oil-filled transformers/reactors is the dissolved gas analysis (DGA) technique [Martin 2002].

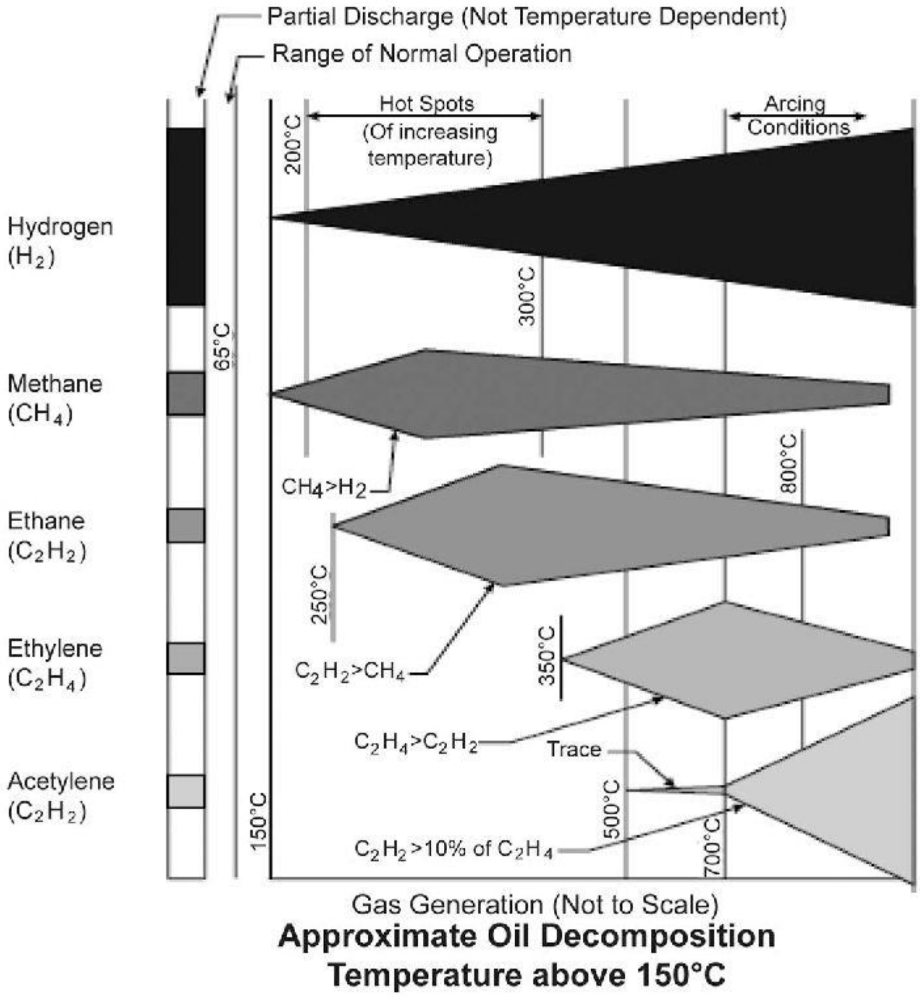


Figure 2-2: Combustible Gas VS Oil Decomposition Temperature [Singh 2010**]**

2.3 Oil Sampling Intervals

Oil sampling is especially important to be done from operating transformers to analyse contamination that can cause hazards in the equipment. The sampling interval does not have a strict procedure that determines the frequency of oil sampling from the transformer. The frequency depends on the objective of the company. Eskom transmission performs its oil sampling every six months. However, if a transformer shows an increase of dissolved gas, the sampling routine will change to a month or a week depending on the severity of fault gases generated [Wang 2003]. The importance of oil samples is to check the trends of dissolved gases developing during the six months and if there is something suspicious on the trending of fault gases, it triggers fault diagnosis. Online frequent oil sampling is much better because it shows the oil results every day and it is easy to observe any abnormalities of gas trending. Knowing which combustible gases produced a consistent rate of production or increases in gas production gives a clear position of what degradation is developing in the transformer [Saha 2003].

Transmission transformer oil sampling data will be seen in the case studies in Chapter 4 for normal sampling and special sampling.

2.4 Methods of Interpreting Gas Concentrations

Various faults generate characteristic combinations of the key gases [Ayalew 2018]. Partial discharges generate hydrogen (H_2), overheating generates ethylene (C_2H_4), stray gassing normally generates at high volume ethane (C_2H_6) and arcing generate large amounts of hydrogen (H_2) and acetylene (C_2H_2) gases released by high concentrations of sparking energy.

Dissolved gas analysis (DGA) has been used widely to identify increasingly serious degradation and different types of faults. The approaches are based on separation, identification, and quantitative determination of the gases at the part per million (PPM) levels [Digiorgio 2005]. The key purpose of the DGA monitoring is to be able to detect early the incipient faults in oil-filled transformers and reactors to give the warning to the operators.

2.4.1 Gas Formation

Any sharp increase of the key gas concentrations reveals a latent problem within the transformer. Table 2-1 which has been derived from ANSI/IEEE C57.104-2008 provides information on the acceptable limit of dissolved gas in the oil-filled transformer. Different gas limits and different fault types produced different gases depending on the level of concentration in the insulation oil.

Table 2-1: Key Gas Concentration [Hamrick 2010]

Gas Description		Key Gas Concentration (in ppm)		
		Normal Limits* (<)	Action Limits** (>)	Potential Fault Type
Hydrogen	H_2	150	1,000	Corona, Arcing
Methane	CH_4	25	80	Sparking
Acetylene	C_2H_2	15	70	Arcing

Ethylene	C_2H_4	20	150	Severe overheating
Ethane	C_2H_6	10	35	Local Overheating
Carbon monoxide	CO	500	1,000	Severe overheating
Carbon dioxide	CO_2	10,000	15,000	Severe overheating
Total Combustibles	TDCG	720	4,630	
*As the value exceeds this limit, sample frequency should be increased with consideration given to planned outage I near term for further evaluation. **As value exceeds this limit, removal of transformer from service should be considered				
This table is derived from information provided within ANSI/IEEE C57.104-2008				

If the oil sample results are within the limit the transformer is considered healthy. If the DGA results showed escalation and the key gases have an increasing trend, this usually requires the more frequent monitoring of the rate of gas production.

Some utilities apply gas concentration in the form of the total combustible gas method [Wang 2003]. It has the advantage of quickly showing a trend and is easily used in the field. The disadvantage of this method is it does not detect the non-combustible gases that developed in the oil, some of which are products of degradation.

Dissolved gas results exceeding the limits should be considered using the approved techniques in the ANSI/IEEE C57.104-2008 and the equivalent “basic Gas Ratio” in the International Electrotechnical (IEC) standards [IEC 60599]. However, none of these published techniques effectively predict incipient failures in the operating transformers with accuracy close to 100% [C57.155-2014].

2.4.2 Gas Ratios

The dynamic pattern of selected ratios of gases can indicate the existence of degradation and to some extent, its relative rate. Therefore, limit values and simple and complex ratios have been proposed to assist the interpretation of the DGA measurements [Wang 2003].

As indicated in Figure 2.1 ratios are simple and easy to use, and selected ratios indicate a condition, such as degradation occurring below or above 300 °C. By combining some ratios into a triangle gives a visual indication of the failure mechanism with specific regions [Sun 2012]. All the diagnosing techniques for DGA methods use different approaches towards diagnosing the problem. It is known that the common gasses used in DGA was presented by [Muhamad 2007]. The conventional accepted methods, Roger's Ratio and Doernenburg Ratio were covered under the IEC and IEEE standards to guide the interpretation of fault gases from DGA data [IEC 60599].

I. Doernenburg Ratio Method

This method utilises the following gas ratios CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4, C_2H_6/C_2H_2 and C_2H_4/C_2H_6 to diagnose the generated dissolved gas in the transformer and it uses the coding schemes to determine the type of the fault such as thermal, corona discharge and arcing faults [Muhamad 2007]. The amount of gases values must exceed the concentration limit to show the fault is active in the transformer oil.

II. Roger's Ratio Method

This method was derived from the Doernenburg method and is recognised by ANSI/IEEE C57.104-2008 as equivalent to the "Basic Gas Ratio" in the International Electrical Commission standards. This method is a technique that uses the four ratios of dissolved gas CH_4/H_2, C_2H_2/C_2H_4, C_2H_6/CH_4 and C_2H_4/C_2H_6 [Muhamad 2007]. This method uses the combination of the coding ratio of the dissolved gas to diagnose the fault generated in the insulation oil from the transformer.

By utilising these four dissolved gas ratios, this method diagnosed faults such as ageing of the insulation, electrical faults which can cause the flash between the conductive parts, low energy discharge and thermal faults in different ranges of temperatures (150˚- 700˚C) [Soni 2016].

Originally, the Roger's ratio method used four ratios and its diagnostic had a limited temperature range of decomposition. The ratio C_2H_6/CH_4 included in IEEE standard C57.104- 1991 was omitted from the IEC code scheme because it leads to invalid interpretation [Reddy 2014].

2.4.3 Graphical Interpretation of Type of Degradation or Fault

The greatest part of fault gas analysis is to use the data gathered from the oil sampling to correctly diagnose the nature of any degradation.

Graphical methods have been used to represent complex gas ratios. The location of a sample result in the graphical space is used to interpret the type of the dominant degradation process.

Michel Duval's Triangle 1 [Duval 2002], the other Duval Triangles 2 to 5, and the Pentagon [Duval 2014] have been used widely as a graphical representation of complex ratios for interpreting the DGA data to identify the types of faults.

The newer method of the LEDT provides more information with regards to normal operating transformers and those moving into an abnormal fault state [Moodley 2012] [Moodley 2017] [Moodley 2018]. Further details of the LEDT method are provided from the different figures below showing how the LEDT interprets the incipient fault and degradation trends.

I. Duval's Triangle 1

The Duval's Triangle 1 is recognised in International Electrical Commission guidelines [IEC 60599] and an IEEE guide for diagnosing fault gases [C57.104-2008]. The Duval Triangle method was shown to be accurate over many years [Geetha 2016]. Duval Triangle 1 Method (DTM) was an improvement of existing of IEC 60599 Ratio Method and IEC TC10 database that represent the DGA results [Golarz 2016]. This method is applied once a potential problem is evident from the accumulated trends in three of the key combustible gases: methane (CH_4), ethylene (C_2H_4,) and acetylene (C_2H_2) taken as a percentage of the total and plotted in a ternary plot [Hamrick 2010]. Subsequently, further triangles have been proposed using different combinations of gases, but they are not widely used because of the later development of the Duval's Pentagon.

II. Duval's Pentagon Method

An approach to present five combustible key gases in mineral oil-filled transformers (H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2) for interpretation in one pentagon graphic was proposed first by Mansour [Mansour 2012]. The graph was re-arranged by Duval [Duval 2014] and is known as the Duval Pentagon.

III. Low Energy Degradation Triangle Method

This method was developed to focus on low energy gas generation at an early stage of degradation, and to plot the movement of the dissolved gas composition away from a normal or ‘healthy’ condition [Moodley 2017]. The Triangle has a clockwise structure like the Duval’s Triangle 1. It uses three dissolved gases CO, CH_4, and H_2, equally weighted.

Decomposition of the cellulose caused by the heating of the active part of the transformer produces dissolved gas such as carbon monoxide (CO), and carbon dioxide (CO2) [Sun 2012]. The base gas CO is generated in relatively low quantities during normal operation. Against this background, early generation of CH_4 and H_2 indicate unusual degradation at higher energy levels move from 0% to 100% from each vertex to identify early state changes from normal to unhealthy. As degradation increases, a vector from the healthy region extends further into the triangle and can be used as a trend indicator over time. The key advantage of this LEDT method is that it gives a clear early indication of the onset of degradation.

2.5 Non-mineral Oil

Starting from the early 1990 ester fluids attracted much attention as a potential alternative to transformer oil [Nurliyana 2016]. This is due to the increase in environmental awareness and a growing interest in biodegradable and non-toxic insulation oil. The use of alternative insulation fluids is demanded in large power transformers, and it was observed during the research that many companies are offering such alternative insulation fluids which are already used in distribution transformers but there is still little experience with those liquids in large power transformers [Eberhardt 2011].

Ester fluid includes two different types of fluids called natural and synthetic ester. Natural ester liquid is from the high oleic fatty acid composition and is derived from rapeseed oil, sunflower oil and sunflower oil [C57.155-2014]. Natural ester oil was normally used for distribution transformers since it was a new insulation medium for cooling and insulating the active part and was less flammable insulation liquid [Bandara 2015]. Synthetic ester is a mixture of combinations of organic acid and alcohol which was also used for the insulation of the transformers and provided cooling with the benefit of less flammable than mineral oil. [Fernandez 2013]

One reason for low use in transmission transformers is that there is not much experience with regards to maintenance history and high confidence of applying limit values for the different dissolved gases [Eberhardt 2011]. In a study investigating use of vegetable oil as an alternative for mineral oil for cooling and insulating purposes, the solid pressboard insulation showed better results in partial discharge and the breakdown values of pressboard [Revathi 2015]. The ester oil produced different types of faults during the operation of the transformers on the network such as thermal and electrical faults and is similar to the fault developed from mineral oil [Borsi 2005].

A detectable gasses study indicated that the paper aged slower in ester fluids than mineral oil especially in high temperatures [Lashbrook 2012]. However, for neopentyl polyol esters, the ageing studies are still lacking. Ester fluids are more hydroscopic than mineral oil which makes to absorb moisture from the solid insulation. The investigation indicated that the esters fluid has a different interaction with water and produce a different number of acids when aged [Lashbrook 2015]. Others found that the natural and synthetic esters were able to absorb 1000ppm of water at room temperature while the water in mineral fluid at room temperature migrates into solid insulation [Hanson 2016] [Pukel 2012a]. The properties of the ester fluids are becoming better known.

Ester oils An investigation identified that gas solubility values for different insulation fluids like mineral oil, esters and silicon are different [Muller 2012]. The results for mineral oil were satisfactory and for the alternative insulation fluids, the calculation did not fit, and the new constant was needed. Among the investigated liquids synthetic esters tend to develop the highest carbon monoxide concentrations with time. Natural esters have a higher initial carbon oxide concentration in comparison with other insulating fluids; however, it does not significantly increase with time under the test conditions. No significant difference could be seen between the ester oil and mineral oil, or Kraft paper and thermally stabilized Kraft paper under the investigated test conditions [Atanasova-Höhlein 2016]. A study found that carbon oxides are produced from the degradation of solid insulation in oil-filled equipment and to a significant extent, especially carbon monoxide, from the insulating liquid itself [Höhlein-Atanasova 2010].

Several studies indicated how dissolved gas generated during performing the testing experiments in the laboratory. The method that has been used worldwide to detect the incipient fault dissolved gas analysis DGA. The ester and mineral oil have no similarities of chemical structure hence the gases esters generated during electrical and thermal fault were same except high amount of DGA compare with mineral oil [Hanson 2016] [Pukel 2012b].

The existing methods such as Roger's Ratio, Doernenburg 's Ratio, Key Gas Method, Duval's Triangle 1, Duval's Pentagons and Low Energy Degradation Triangle were all utilised in the previous research studies to diagnose incipient faults in transformers with mineral oil. On a study performed it was found that Roger's Ratio is not suitable to be used for PO and RBO for diagnose the electrical fault. The ratio of C2H6/CH4 was eliminated from Roger's Ratio Method for diagnose the fault because it indicated limited temperature range for decomposition of insulation [Hamid 2017]. Duval Triangle and Roger's ratio method were able to detect the fault on generated thermal stress in esters mean while the Dornenburg ratio method and IEC method failed to predict the overheating fault [Gomez 2014].

Doernenburg ratio method can diagnose fault from the transformer filled with natural ester oil. The type of fault this method can diagnose such as thermal, partial discharge and arcing faults using ratio coding scheme. However, this method is not suitable to diagnose arching fault generated from the rice bran oil (RBO) but it can diagnose the fault generated from the palm oil (PO) [Hamid 2017 a]. Doernenburg ratio method and IEC method failed to predict the overheating fault.

There are five gas ratios that to show the type of the fault generated in the ester oil according with the study done by [Hamid 2017 b]. It appears Duval's Pentagons and Low Energy Degradation Triangle (LEDT) have not been extensively applied to the ester oil because due to these being relatively new diagnosis methods.

Some researchers indicated that methods using the coding method were more accurate for diagnosing the generated faults and for making predictions of their decision. The disadvantage of the coding method is that if the values of the faulted gases are exceeding the limits, these methods are not able to provide predictions on both fluid insulation esters and mineral oil.

The comparisons of the investigation of DGA between mineral and ester oil with the electrical and thermal fault simulation were performed [Perrier 2012]. The Duval's Triangle 1 method for thermal and electrical faults provide good findings when compared to other diagnostic methods. The Duval's Triangle 1 method need adjustment in order to interpret the H_2 associated with C_2H_6 because in many cases ethane is indicating stray gassing in ester oil with high values.

Duval's Pentagon's method was evaluated on diagnosing the ester oil and was found to be highly accurate when compared to the Duval's Triangle 1 method [Meira 2019]. Furthermore, this method overcomes the drawback of the Duval's Triangle 1, especial with low thermal and discharge faults.

When comparing the existing methods such as Roger's Ratio, Doernenburg 's Ratio, Key Gas Method, Duval's Triangle 1 on different types of faults for electrical and thermal tests, concluded that Duval's Triangle 1 and IEC methods are preferable than the IEEE coding method [Imad-U-Khan 2007].

2.6 Conclusions

The above-mentioned methods will be evaluated for their advantages and disadvantages for detecting incipient fault from the DGA data of the failed transformers/reactors from the Eskom transmission network. All transmission transformers/reactors were mineral oil filled.

In chapter 3 all techniques and methods mentioned in this study will be further discussed from their description and how to detect the incipient fault generated in the oil-filled transformers/reactors.

3 CHAPTER 3: PROPOSAL FOR LEDT ASSESSMENT USING TRANSMISSION TRANSFORMERS

3.1 Introduction

Chapter 2 reviewed the existing literature to identify available answers to the research questions and to identify methods and data relevant to this research. It was also identified that there is not much experience with regards to dissolved gas analysis with to alternative insulation liquids like ester oils. This area is still under development in quantifying high confidence levels in the diagnosis.

This chapter describes in greater detail how the LEDT method is applied to derive the maximum benefit from its advantages for the early detection of incipient faults.

The LEDT method is a relatively new method that was developed using DGA data and case studies of generator transformers in South Africa. It has been extended in preliminary studies to the MEDT model which identified the insulation degradation based on dissolved gases characteristic of medium energy degradation. For this purpose, it is useful to understand some of the relationships that underlie the LEDT.

3.2 LEDT Method

3.2.1 Concept for LEDT Method

The LEDT method was based on the hypothesis that dissolved gases generated at low energy levels could be most indicative of the earliest initiation of degradation in a power transformer and that a trend line would indicate worsening conditions. The LEDT method was tested on Eskom generation power transformers with positive results [Moodley 2017] and became a useful operational tool.

The LEDT method was based on the three key gases because it was known that thermal faults start with the production of H_2 and CH_4 before progressing to higher energy thermal faults [Ward 2003]. The LEDT also uses the H_2:CH_4 ratio which usually (though not in the case of lightning strikes) represents the start of dielectric faults, characterised by cold partial discharge and small arcs, without progressing to more major faults of arcs discharges that typically form C_2H_2 . The other ratios in the LEDT are H_2:CO and CH_4:CO which incorporates the ‘normal’ degradation of cellulose-based insulation at typical operating temperatures.

This method was generated to fit these relationships in a ternary plot where the three dissolved gases form the sides of the triangle and are represented as percentages having a summation of 100%. The calculation of each % is:

%ppm=(ppm of gas1/sum ppm of all three gases)x100.

Each side of the triangle has a zero starting point vertex reaching 100 % on the far side. Increasing gas concentration of the three parameters with increasing degradation is generally clockwise. Figure 3-1 provides an indication of the general layout of the triangle, with an example of 40 ppm hydrogen, 10 ppm methane, and 150 ppm carbon monoxide, each expressed as percentage the sum of 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 [Moodley 2017].

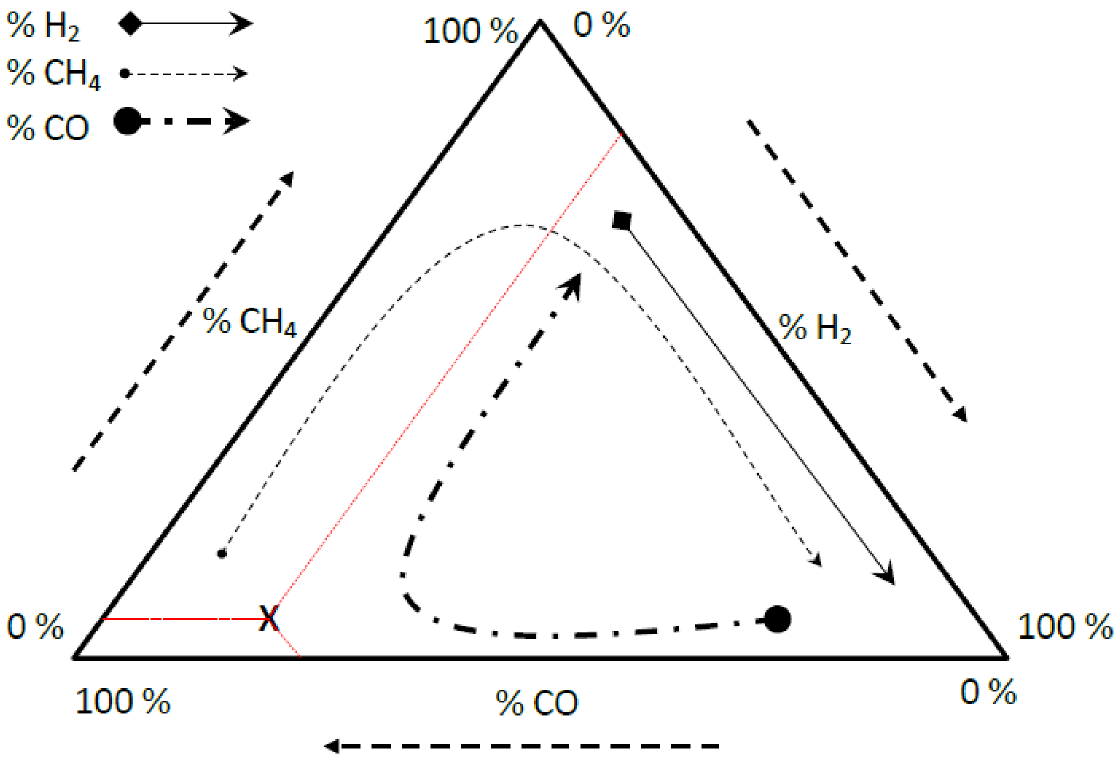


Figure 3-1: LEDT Concept [Moodley 2012, 2017]

The advantage of the LEDT method is that it provides an interpretation of the oil samples in the absence of significant degradation. It has a normal condition region (bottom left) and regions where an incipient fault progresses towards more likely failure the further the trend line moves upward and to the right. It gives a transformer engineer time to prepare maintenance outages.

Based on IEC 60599 and IEEE C57.104-2008, H_2 production increases constantly with increased fault energy [Mehta 2016]. Methane is produced predominantly as the result of the breakdown of oil from temperatures in the range 90°C – 500°C. With higher temperature degradation, the level of methane to decrease and ethylene and acetylene form.

The CO and CO_2 evolution is usually related to the thermal breakdown of paper at moderate temperatures starting as low as 110°C [Hino 1972] [Saito 1959] [Yoshida 1987] and continuing at temperatures up to 700°C. As the degradation energy increases, the percentage of carbon monoxide initially increases, reaches a maximum, and declines [Duval 2014].

3.2.2 R-Value Trend

The LEDT method has a simple indicator of insulation degradation from a normal state to the early stage of commencement with further progression [Moodley 2017].

The LEDT plot has a normal/healthy region at the bottom left vertex taken as point A (0, 0) in Figure 3-2. The magnitude (R-value) of the (R, ϴ) coordinate indicating the severity of the evolving degradation is calculated as follows:

$$X = r \cos \Theta \qquad [1]$$

$$Y = r \sin \Theta \qquad [2]$$

$$R = sqrt(X^2 + Y^2) \qquad [3]$$

The R-value trend with time is developed directly from the LEDT plot.

From empirical data the normal/healthy region of the LEDT was initially set as R=0.17, but with more operational experience it is now considered in Eskom to be $R < 0.13$, representing the point (H_2, CH_4, CO) adjusted to 7.5%, 7.5% and 85% respectively. When the R-value exceeds the value of 0.13, close monitoring is required as this is an indication of unacceptable insulation degradation.

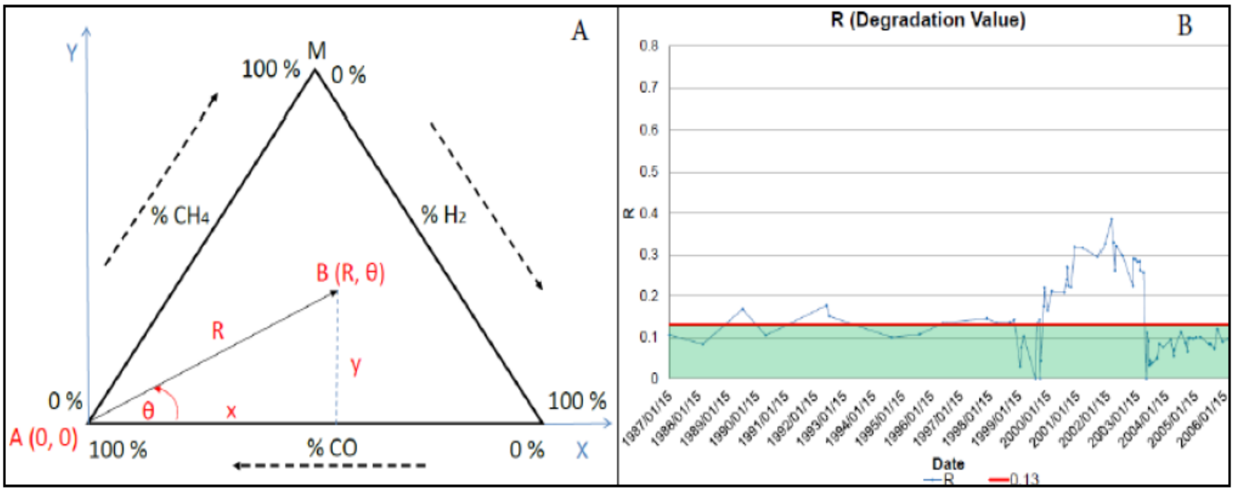


Figure 3-2: LEDT as a Polar Plot [Moodley 2017]

3.2.3 LEDT Regions in the Triangle

A benefit of the LEDT is that it has regions that indicate different types of faults and indicates when different modes of degradation generally start. Figure 3-3 shows the different regions for the low energy degradation triangle. The demarcation of the regions is comparable with similar regions in the Duval's Triangle 1. In addition, there is a normal region where the transformer is in a satisfactory condition and there is no need for frequent monitoring. The Duval's Triangle 1 does not have a region corresponding to the healthy region of the LEDT.

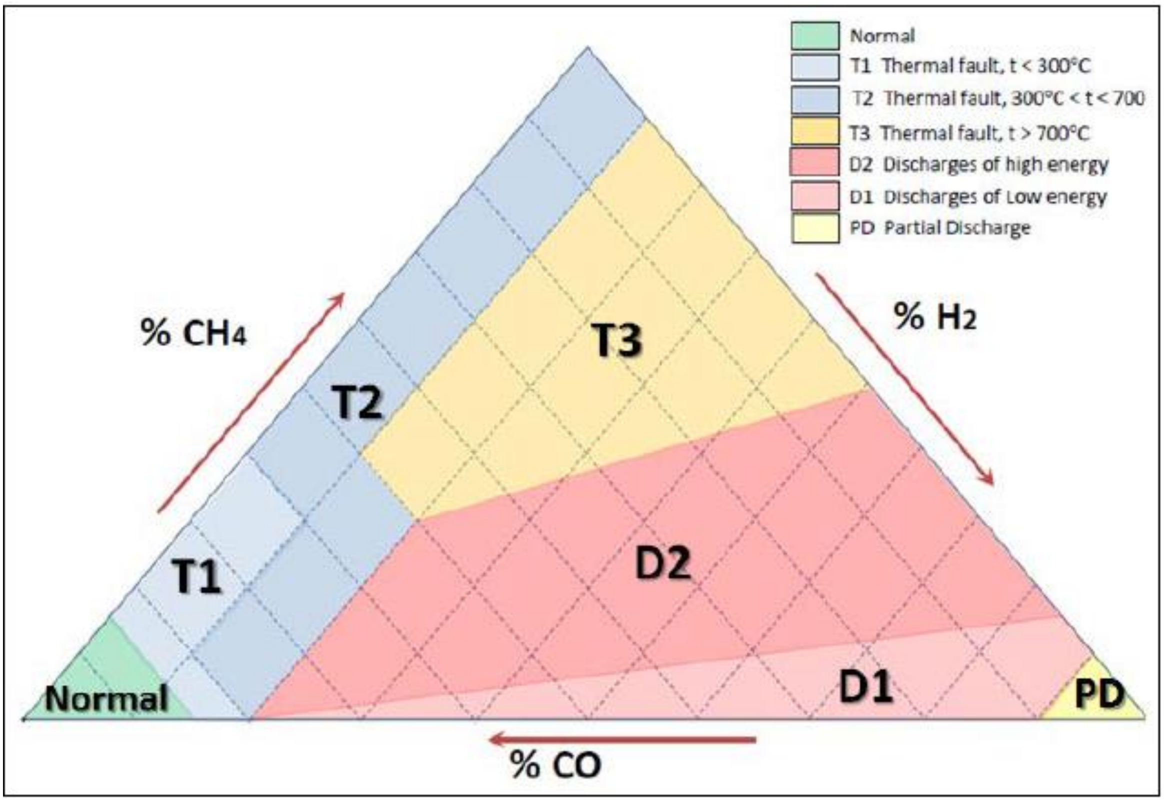


Figure 3-3: LEDT Fault Regions

Transformers operating at normal temperature usually develop higher percentages of CO when compared to other key combustible gases. When faults develop the percentage of H_2 and CH_4 tend to increase due to the breakdown of oil. For thermal faults the level of CH_4 increases and for discharges the levels of H_2 tend to increase in comparison to the CO levels. This causes the trend in the LEDT to move to the top or right of the triangle depending on the fault condition.

The Normal region is indicated as the green region which is on the lower left vertex of the LEDT. Movement upward along the %CH_4 axis is characterised by thermal heating with elevated %CH_4 and relatively constant %H_2. This region is composed of both T1 (thermal fault, t < 300 °C) and T2 (thermal fault, 300 °C < t < 700 °C) type faults and may vary accordingly [Moodley 2018].

The fault progression then leads further into the triangle which can enter the regions of D1 (discharges of low energy), D2 (discharges of high energy) and T3 (thermal faults, t > 700 °C). Progression into these regions is characterised by significant increase in the percentage hydrogen and methane in differing proportions. Partial discharges are noted in the region PD which is for percentage hydrogen levels greater than 90% [Moodley 2018].

Therefore, LEDT gives an engineer better understanding of the condition or faults within the power transformer to be able to arrange for the necessary investigations.

3.2.4 Combustible Gas Trend

The example in Figure 3-4 shows a typical combustible gas trend of the key gases. It can be observed that the trends are very erratic with no clear diagnosis apart from general trend increases or decreases. There are also no interrelationships between the key gases.

The benefit of the LEDT is that even with erratic dissolved gas results it is still able to maintain the diagnosis according to the percentage of gasses and to clearly indicated the prevailing fault condition. This is evident in the corresponding LEDT representation of the combustible gas trend in Figure 3-4.

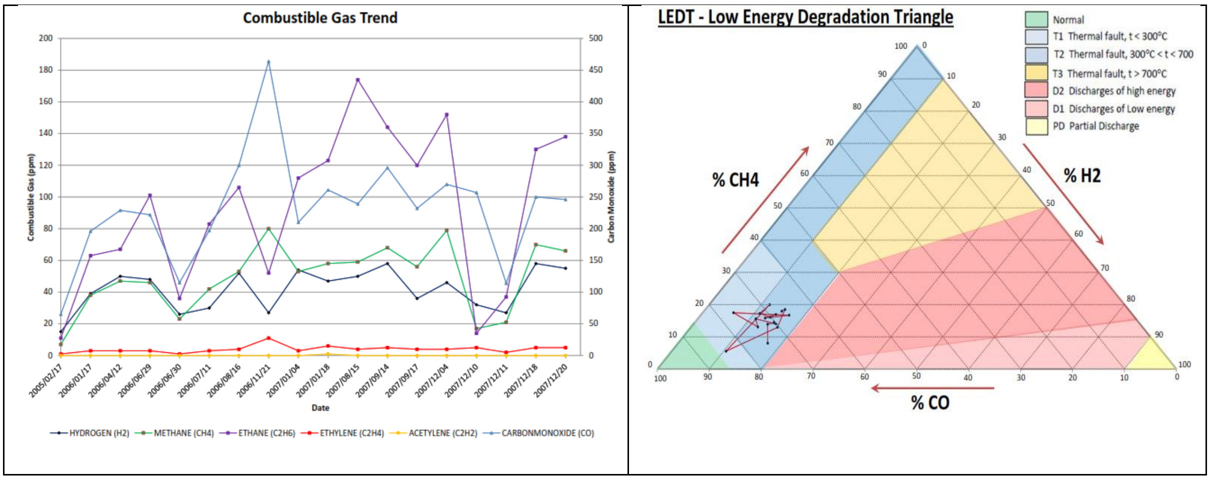


Figure 3-4: Combustible Gas Trend Versus LEDT Representation

3.2.5 Extension of LEDT concept to MEDT

The LEDT uses the gases CH_4 and H_2 moderated by the CO. Three other gasses are associated with degradation at higher levels of energy: C_2H_4, C_2H_6, and C_2H_2. It is postulated that useful information might be derived from a complex ratio with two of these gases.

Based on the same logic of identifying the onset of low energy degradation, the LEDT technique can be extended to the Medium Energy Degradation Triangle (MEDT) method to indicate the onset and trend of degradation happening at higher local temperatures.

Combinations of gases with CO_2, C_2H_6, and C_2H_4 had been tested on the Eskom GSUs [Moodley 2017] but without successful outcomes. The possibility that an MEDT with ethane (C_2H_6) or ethylene (C_2H_4) on a carbon monoxide (CO) base might be a useful diagnostic tool on transmission transformers was of interest.

The MEDT construction is like the LEDT method, and the diagnosis of degradation processes are similar though using different key gases ratios.

See an example in Figure 3-5, both MEDT and associated R-Value indicated a medium energy incipient fault in the operating transformer with the R-Value indicating a developing fault from the normal region up to where the fault was in the visible state to be investigated.

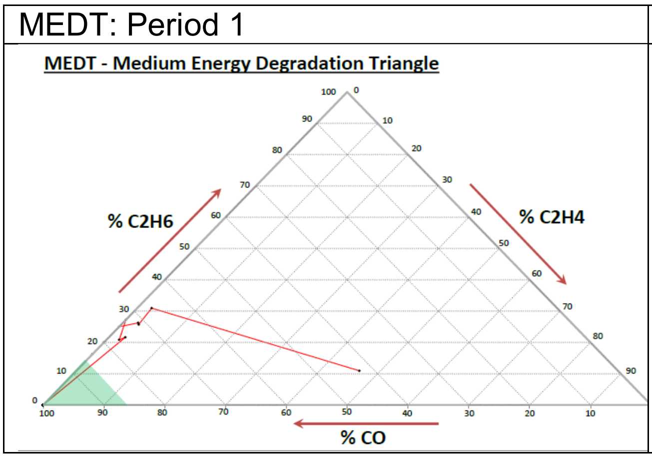
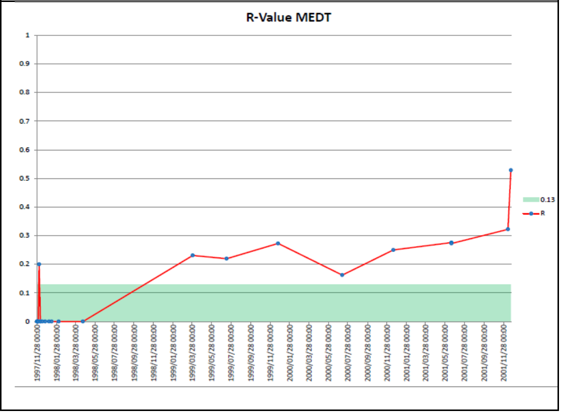
MEDT: Period 1	R-Value
	

Figure 3-5: MEDT and R-Value

3.3 Proposed Case Study Protocol

The concepts outlined in sections 3.2 and 3.3 will be tested on case studies using DGA records from the first test oil results taken after the transformer was commissioned. This will test the application of LEDT and MEDT to validate the interpretation and relevant diagnosis.

The main part of this study is the application of LEDT on transmission transformers as these transformers operate at generally lower temperatures than GSU transformers. The second part of this study is to verify the benefits of the MEDT method.

Seven case studies of failed transmission transformers were developed. The transformers were selected of the basis that post-fault inspection indicated their failure was due to thermal and electrical faults. The testing protocol was:

- Describe the transformer’s history.
- Present the DGA measurement record.
- Apply and interpret the Rogers and Doernenburg ratios, The Duval’s Triangle 1, and Pentagon, and the LEDT and MEDT.
- Compare the advantages and disadvantages of these different approaches to DGA interpretation with each other and with the root cause analysis of inspected transformers.

3.4 Summary

The theory underlying the LEDT method using three key gases CH_4, H_2 and CO on each side of the triangular plot explains the LEDT’s advantage of detecting early stages of degradation and trends towards faults.

The LEDT approach has been extended to the MEDT on the same theoretical basis for the purpose of identifying a transition to medium energy degradation.

In chapter 4 the various DGA interpretations will be tested and compared to the data from previous failures (case studies) from transmission transformers and reactors.

4 CHAPTER 4: CASE STUDIES

Chapter 4 utilises dissolved gas analysis (DGA) which is one of the most recognised methods worldwide for detecting incipient faults from the oil-filled transformers and reactors [Martin 2010].

The case studies will first investigate the four commonly accepted methods to diagnose incipient faults in the oil filled transformers and reactors. These methods are Roger's Ratio Method, Doernenberg's Ratio Method, Duval's Triangle 1, and Duval's Pentagon 1. The newer dissolved gas analysis methods, LEDT Method and MEDT Method will then be assessed and compared to identify any advantages that they may offer for fault diagnosis.

The analysis consists of seven case studies based on real failures as identified in Eskom Transmission transformers and reactors. The main objective of this chapter to validate the LEDT method as an effective tool for identifying low energy degradation and incipient fault identification. **Case Study A: 275/132/22kV: 250MVA, YOM: 2008**

4.1.1 Background and Root Cause Analysis

This transformer was manufactured in 2008 and in 2010 it was moved from the strategic stores to the transmission substation for installation on the North-Eastern Grid. The transformer was loaded at no more than 50% of the MVA rating according to the transmission strategy of N-1 capacity.

The transformer had an oil type on–line tap changer without a selector and diverter compartment, but the selector was open/connected to the main tank. A gas analyser was connected to the bottom of the main tank valve. The first commissioning oil samples were taken in November 2010.

In January 2011 the combustible gases started escalating. In July 2011, the online gas analyser identified further escalation of dissolved gases. In September 2012 and May 2013 further increases were evident. The transformer was taken out of service from the period 27 May – 15 July 2013. The oil was processed, and an internal inspection was carried out. When the transformer was returned to service after 15 July 2013 the carbon monoxide levels started to increase consistently. The transformer was oil sampled again and it was kept under close monitoring.

When the gases were increasing the load was reduced and oil samples were taken to confirm the gas analyser.

4.1.2 Case Study A - Combustible Gas Trend

Figure 4-1 provides a combustible gas trend of the dissolved gas results over the period.

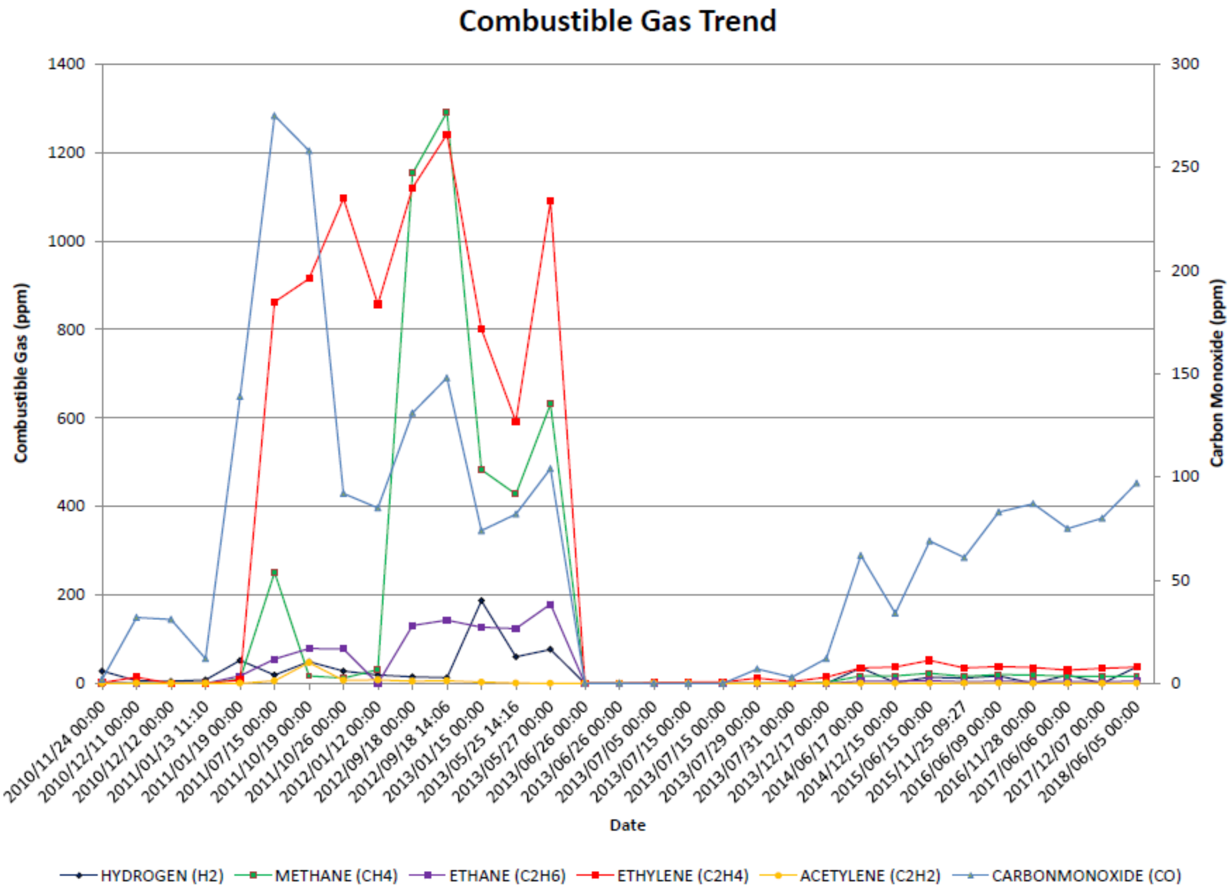


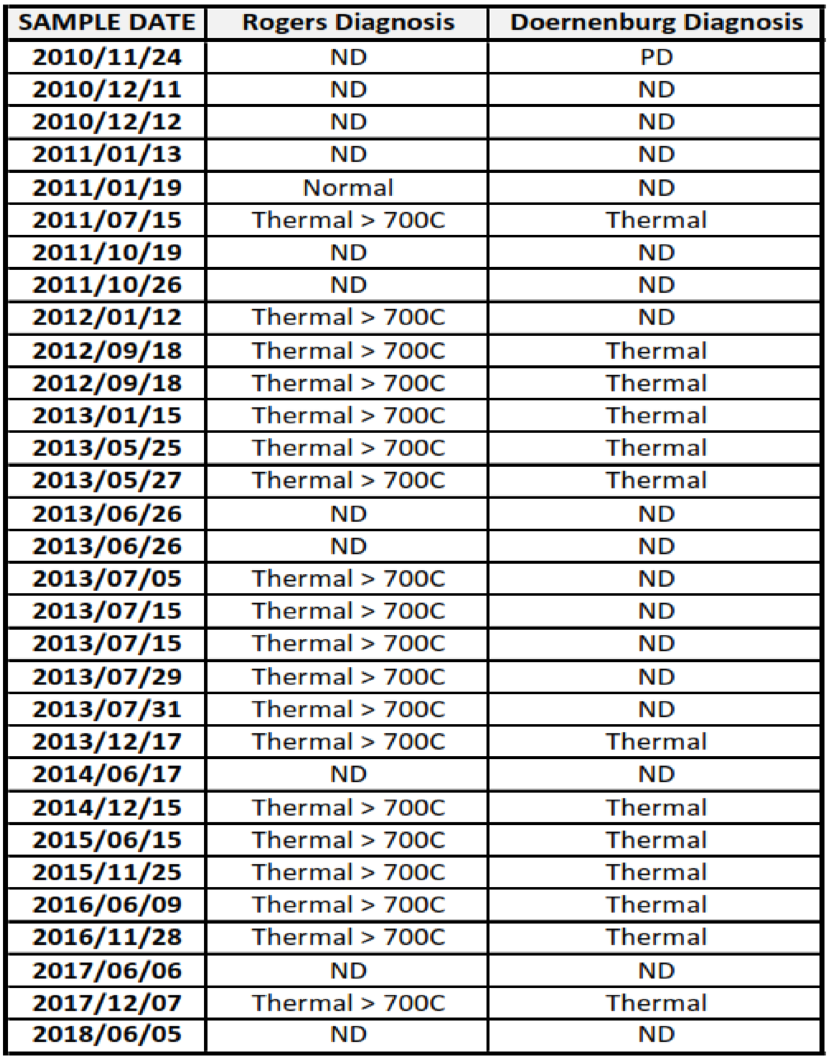
Figure 4-1: Case Study A - Combustible Gas Trend

From the trend it is observed that after the first year the transformer started gassing with elevated levels of Carbon Monoxide, Methane and Ethylene. The transformer was taken out in June 2013 for inspection. This was period 1. From the oil samples after it was returned to service it is identified that the levels of Carbon Monoxide started to increase again. This was taken as period 2.

4.1.3 Case Study A - Rogers and Doernenburg Ratio Methods

Rogers and Doernenburg ratios were taken for the full sample range as indicated in the Table 4-1 below. ND represents no diagnosis where Roger’s Ratio Method had 35% and Doernenburg method had 55% ND diagnosis. It is observed that Roger’s ratio had only one diagnosis of “thermal > 700°C”. Doernenburg ratio had a diagnosis of “PD” and “Thermal”. The dynamic pattern of selected ratios of gases can indicate the existence of degradation and to some extent, its relative rate; so, limit values and simple and complex ratios have been proposed to assist the interpretation of the DGA measurements [Wang 2007].

Table 4-1: Case Study A - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
2010/11/24	ND	PD
2010/12/11	ND	ND
2010/12/12	ND	ND
2011/01/13	ND	ND
2011/01/19	Normal	ND
2011/07/15	Thermal > 700C	Thermal
2011/10/19	ND	ND
2011/10/26	ND	ND
2012/01/12	Thermal > 700C	ND
2012/09/18	Thermal > 700C	Thermal
2012/09/18	Thermal > 700C	Thermal
2013/01/15	Thermal > 700C	Thermal
2013/05/25	Thermal > 700C	Thermal
2013/05/27	Thermal > 700C	Thermal
2013/06/26	ND	ND
2013/06/26	ND	ND
2013/07/05	Thermal > 700C	ND
2013/07/15	Thermal > 700C	ND
2013/07/15	Thermal > 700C	ND
2013/07/29	Thermal > 700C	ND
2013/07/31	Thermal > 700C	ND
2013/12/17	Thermal > 700C	Thermal
2014/06/17	ND	ND
2014/12/15	Thermal > 700C	Thermal
2015/06/15	Thermal > 700C	Thermal
2015/11/25	Thermal > 700C	Thermal
2016/06/09	Thermal > 700C	Thermal
2016/11/28	Thermal > 700C	Thermal
2017/06/06	ND	ND
2017/12/07	Thermal > 700C	Thermal
2018/06/05	ND	ND

4.1.4 Case Study A - Duval’s Triangle 1

The Duval’s Triangle 1 method for Period 1 (Figure 4-2) indicated the transformer started with discharge and because the transformer was not attended too, the fault gases escalate to high thermal energy greater than 700°C.

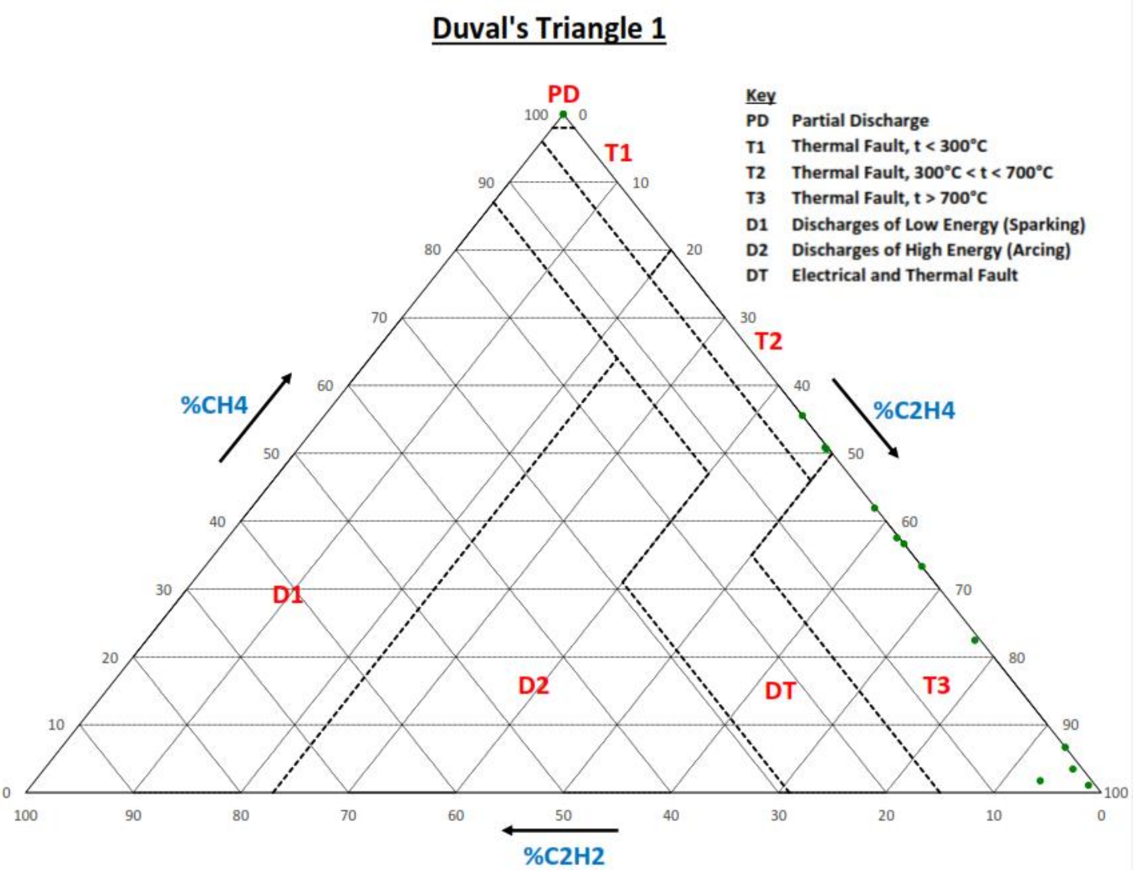


Figure 4-2: Case Study A - Duval’s Triangle 1 - Period 1

Period 2 (Figure 4-3) indicated that the fault was on T3 region where thermal fault exceeded 700°C. This supported the LEDT diagnosis. The cause of the escalation of fault gases is thermal fault generated on the active part of the transformer.

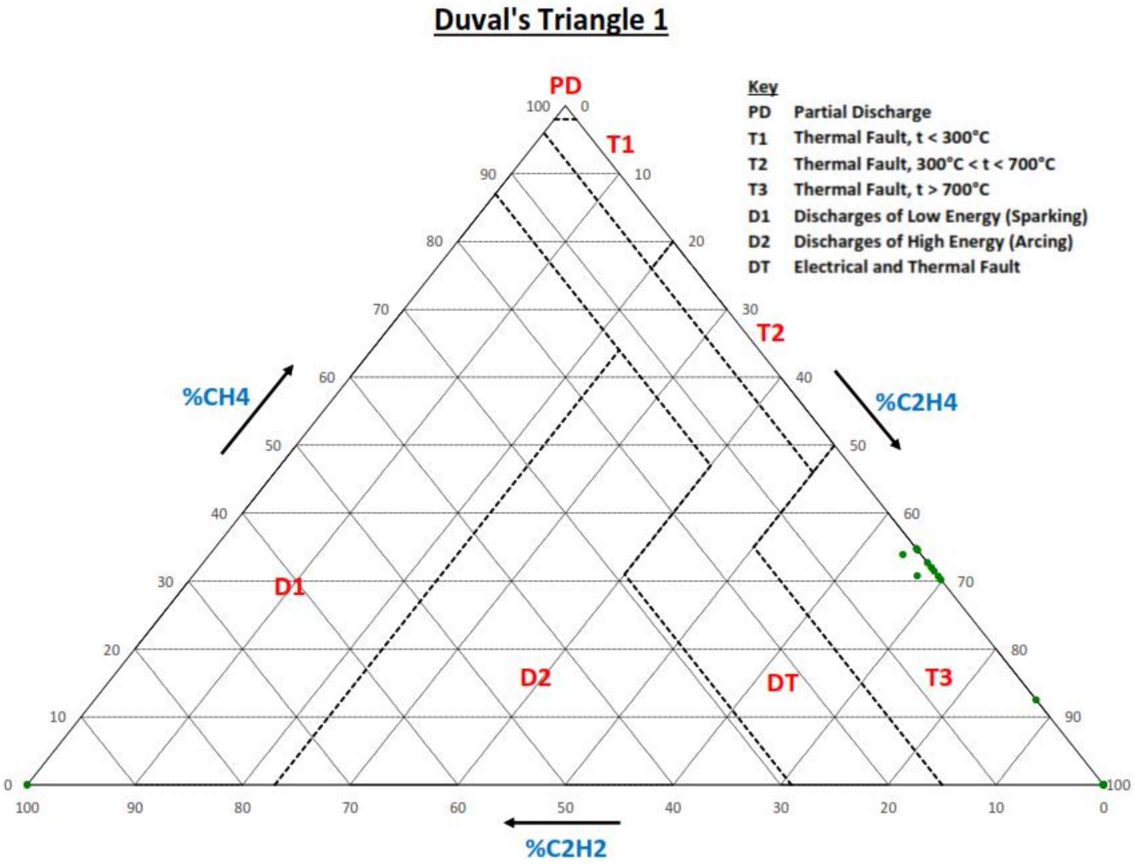


Figure 4-3: Case Study A - Duval's Triangle 1 - Period 2

4.1.5 Case Study A - Duval's Pentagon Method 1

The Duval's Pentagon 1 for period 1 (Figure 4-4) indicated a T1 and T3 fault condition which suggests an overheating problem. The fault at T3 region is for temperatures greater than > 700˚C. Duval's Pentagon 1 Method diagnoses complemented by the diagnoses result from Duval's Triangle 1 on Figure 4-3 for Period 1 and Period 2.

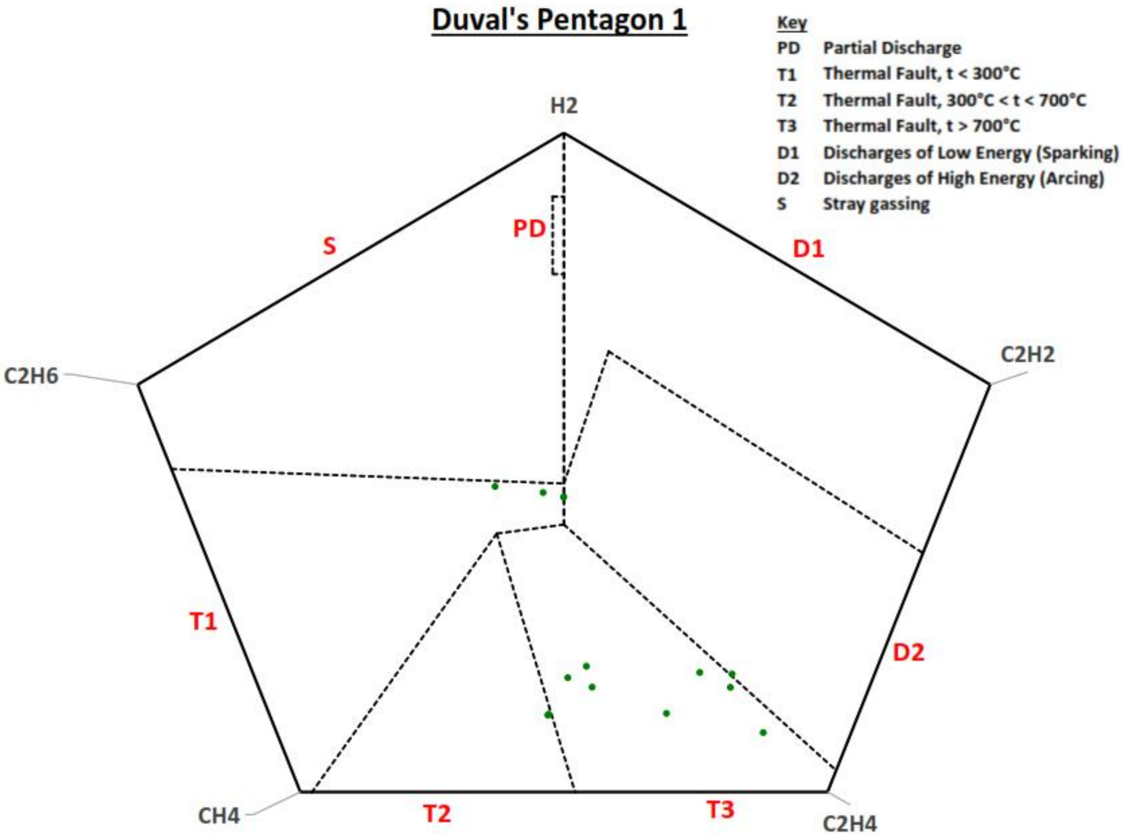


Figure 4-4: Case Study A - Duval’s Pentagon 1 – Period 1

The Duval’s Pentagon 1 for period 2 (Figure 4-5) indicated mainly a T3 fault condition which was in line with the Duval’s Triangle 1 method.

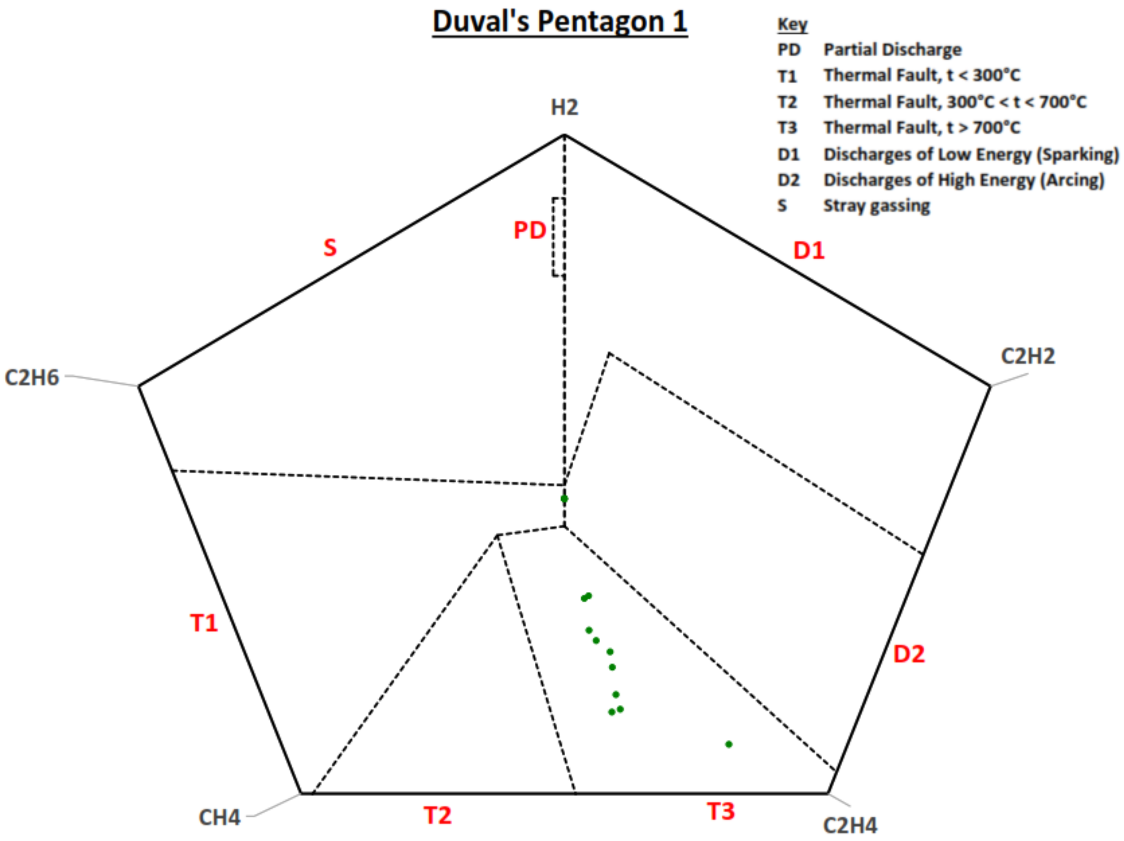


Figure 4-5: Case Study A - Duval’s Pentagon 1 – Period 2

4.1.6 Case Study A - LEDT and R-Value Trend

The LEDT is presented for two periods: before and after it was inspected in June 2013. The LEDT during Period 1 showed that this transformer probably had a defect on the active part before the first energization. The combustible gases escalated until the transformer was taken out from service.

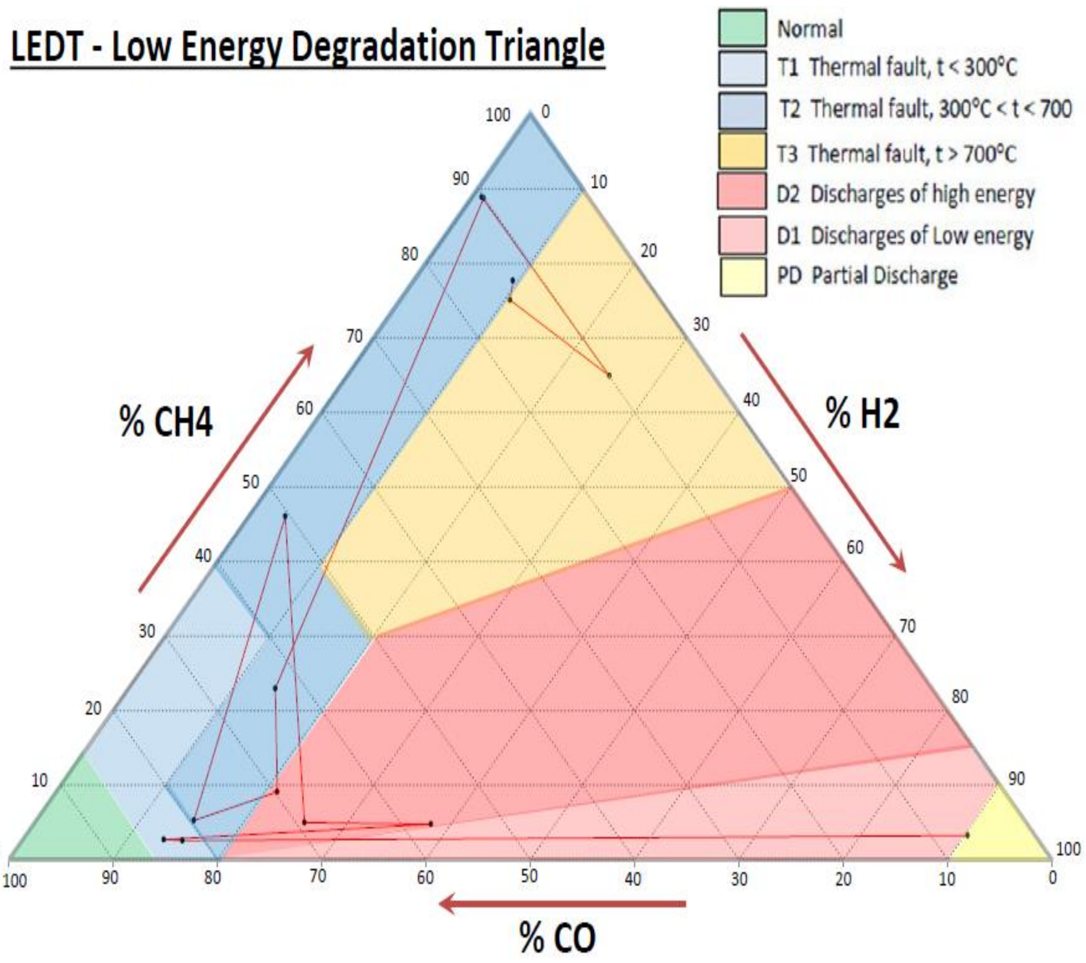


Figure 4-6: Case Study A - LEDT - Period 1

On the first oil samples of the 24th of November 2010, the LEDT for Period 1 indicated that the transformer was experiencing a thermal fault. The first commissioning oil sample indicated a PD fault which then quickly progressed to a T1 fault which then progressed to D2 discharges as the fault developed. From the 5th sample the fault then became thermal in nature progress from T2 to a T3 Thermal fault.

The internal inspection revealed a poor connection of the copper link on the selector switch. All the regions involved confirm the discharges and overheating problem that was related to the development of the fault.

Figure 4-7 depicts the R-Value providing a clear trend of the fault development which was present from first commissioning.

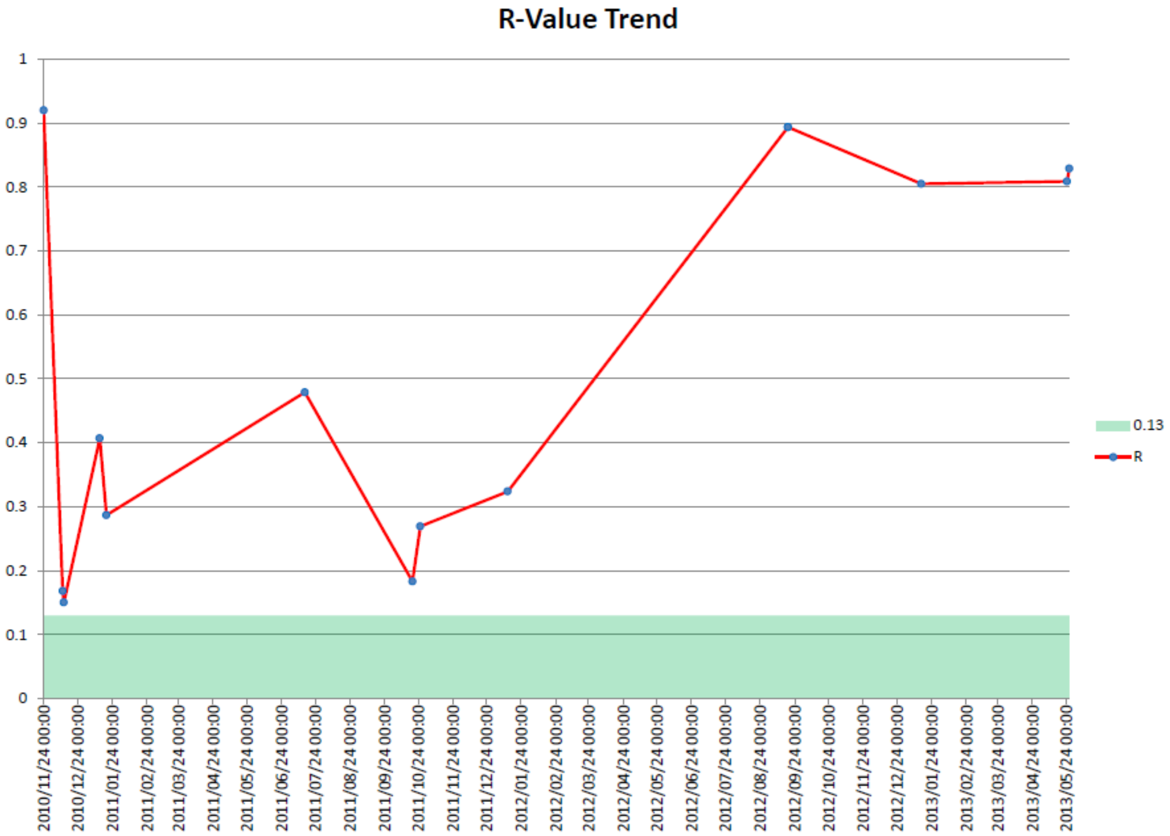


Figure 4-7: Case Study A - R-Value - Period 1

In Period 2, when the transformer was return to service after fixing the defect in the selector switch, all combustible gases were normal except hydrogen H_2 which was escalating and indicating that a possibly different defect was not solved. This defect might have been the same as or similar to the defect in Period 1.

The LEDT for Period 2 showed that, after sorting out the problem on the selector switch, the gas generation started at a normal region and escalate to other regions. That means, the problem was not properly repaired, or a second defect existed. The fault immediately when to the T1 and T2 regions indicating a thermal fault with some discharges in oil.

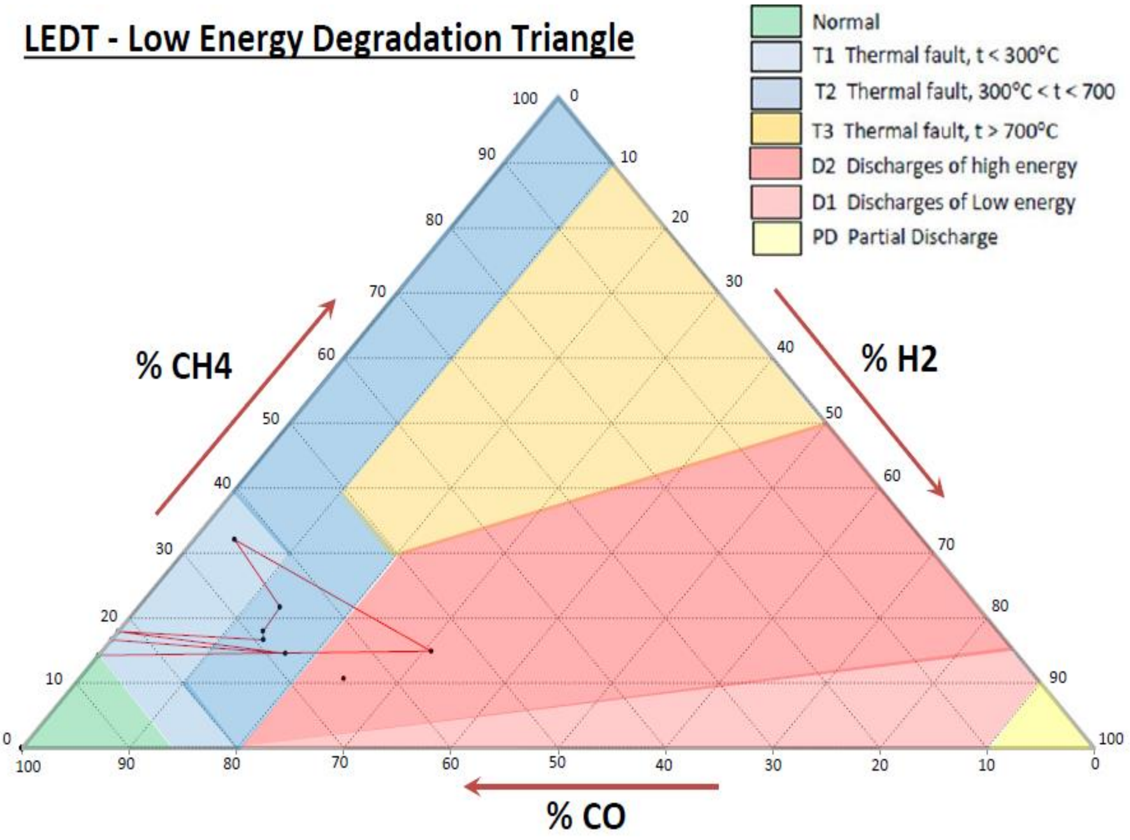


Figure 4-8: Case Study A - LEDT Period 2

The R-Value Trend in Figure 4-9 supported the fault progression trend over time.

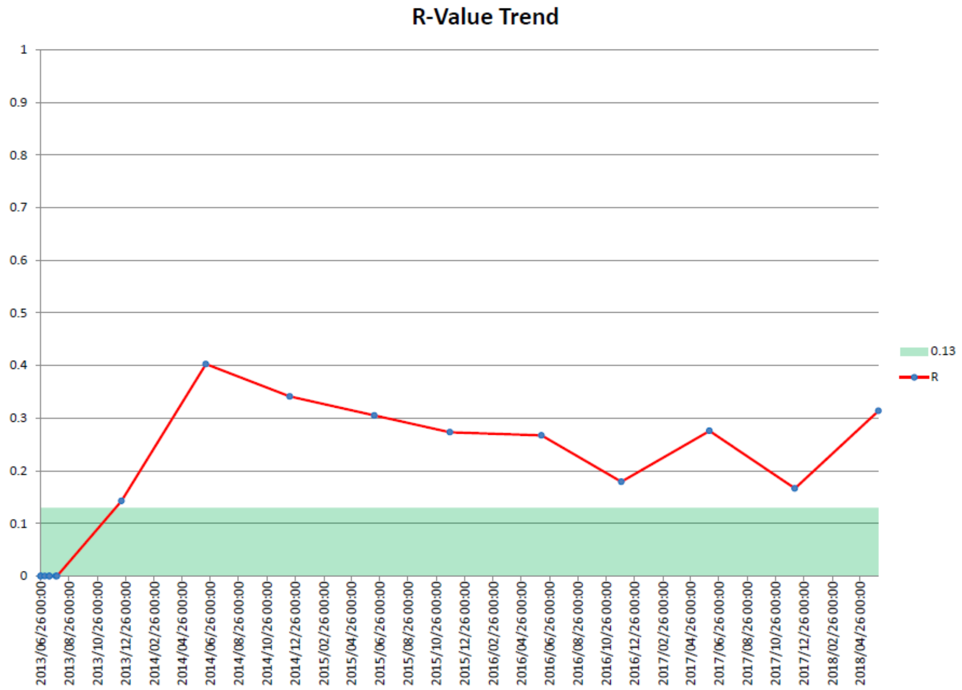


Figure 4-9: Case Study A - LEDT and R-Value - Period 2

4.1.7 Case Study A - Extension to MEDT

The MEDT for Period 1, as depicted in Figure 4-10, indicates a complementary diagnosis with that of the LEDT Period 1 diagnostic results. In December 2010, the transformer was taken out of service to perform 380V electrical tests.

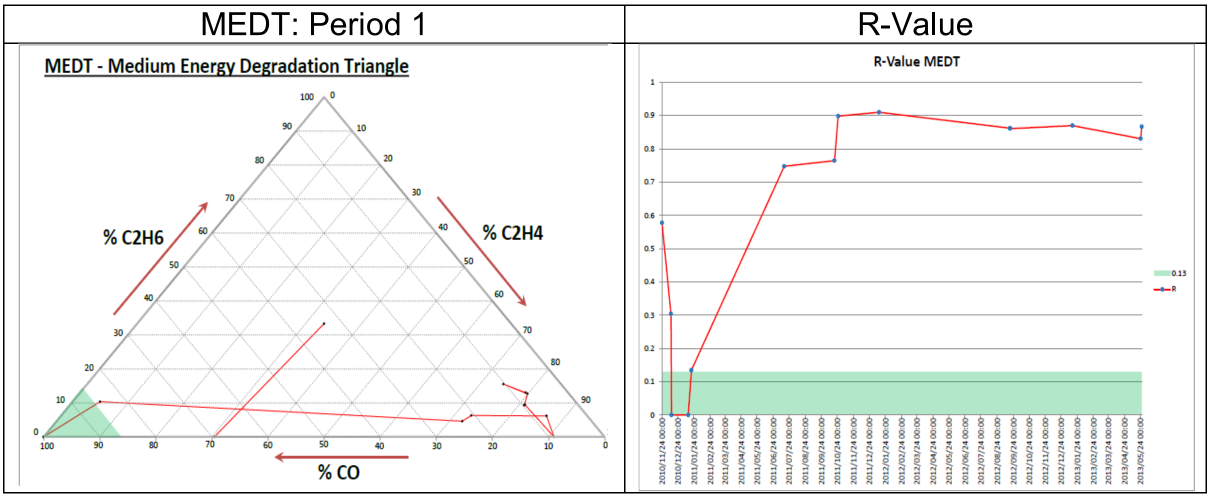


Figure 4-10: Case Study A - MEDT and R-Value - Period 1

MEDT Period 2 indicated activities developing outside the normal stage and R-Value was confirmed. The fault involve in this case is the combination of voltage stress and thermal as confirmed by LEDT Period 2 (Figure 4-11) and Figure 4-12 showed discolouring signs on the failed component.

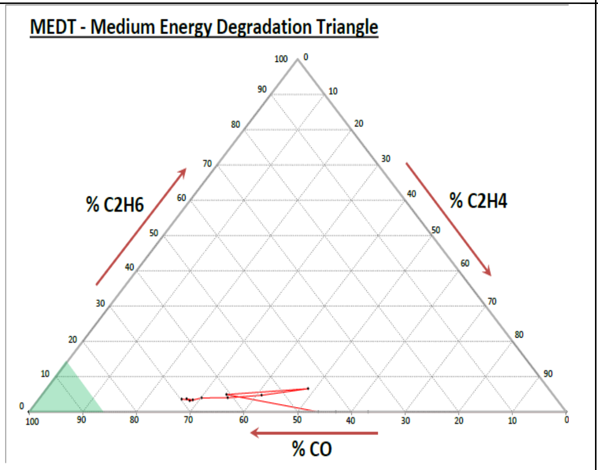
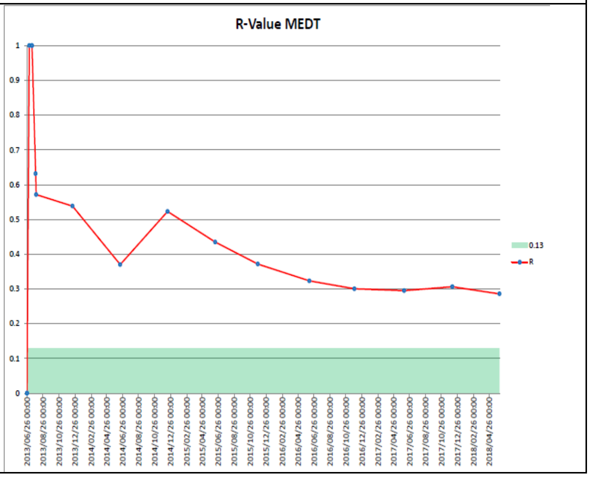
MEDT: Period 2	R-Value
	

Figure 4-11: Case Study A - MEDT and R-Value - Period 2

4.1.8 Case Study A: Evaluation

An internal inspection was conducted on the transmission substation transformer. Severe overheating was observed on the copper link on the tap-changer for the A-phase selector switch. See the damage component in Figure 4-12.

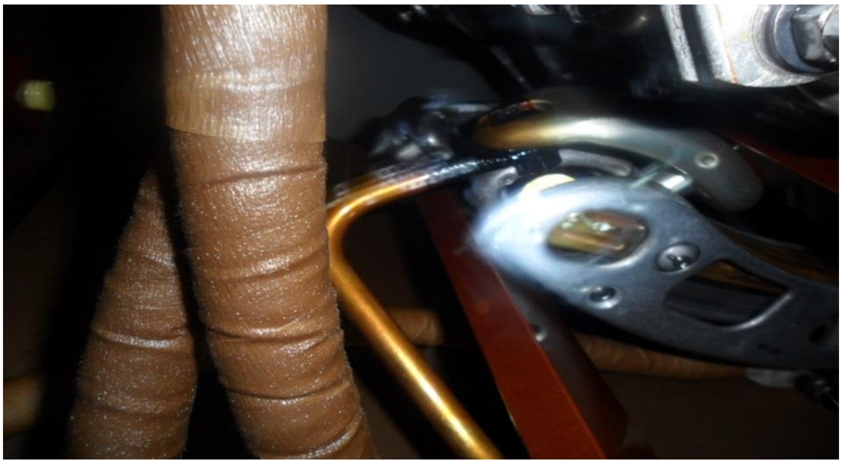


Figure 4-12: Signs of overheating on copper link A-phase selector switch

In 2013 the transformer was de-energized for 380V tests to be performed to investigate the cause of generated fault gases and DC winding test indicated the deviations on the A-phase selector switch. Figure 4-13 shows the test results of the DC winding test that was performed before draining the oil from the transformer, the graph indicating the fault on the A-phase.

Tapping position	Phase to Star point A-N (mΩ)	B-N (mΩ)	C-N (mΩ)
Tap 1	358.9	334.3	333.1
Tap 2	356.9	332	330.9
Tap 3	354.4	329.6	328.4
Tap 4	352.1	327.2	326.1
Tap 5	349.7	324.9	323.7
Tap 6	347.5	322.6	321.4
Tap 7	345	320	319.1
Tap 8	342.8	317.9	316.7
Tap 9A	340.3	315.5	314.3
Tap 9B	314.1	315.3	314.1
Tap 9C	314.3	316	314.4
Tap 10	316.7	318.1	316.9
Tap 11	319	320.4	319.2
Tap 12	321.3	322.7	321.5
Tap 13	323.7	325.1	323.8
Tap 14	326	327.4	326.1
Tap 15	328.4	329.8	328.6
Tap 16	330.7	332	330.8
Tap 17	333.1	334.5	333.2

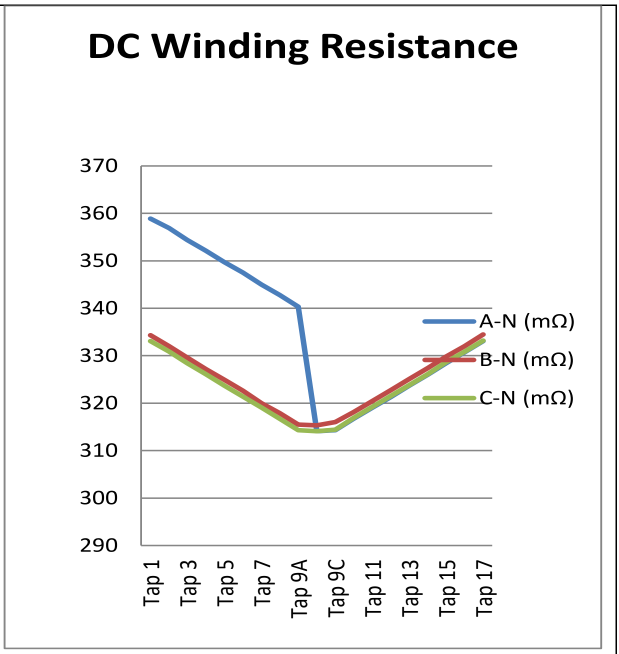


Figure 4-13: DC Winding Resistance results

The DC winding resistance test results indicated that A-phase had high resistance from tap position 1 to 9A compared with the other phases. From tap 9B to 17 the test results were matching with the other three phases. The high DC resistance indicates that there is a partial discontinuity or such as a loose connection which was confirmed by the discolouration of the copper link. The graph confirmed the loose connection on the tap changer. This was the reason for the transformer gassing again after repairs of tap changer due to the high resistance on A-phase, from tap position 1 to 9A.

In this case study, the Roger's and Doernenburg ratio methods do not offer a consistent interpretation of the degradation or its trend and had very high percentages of no diagnosis. The Duval's Triangle 1 and Pentagon methods indicate the type of fault occurring but there is no indication of trend progression of the fault. The LEDT and MEDT each with R-Value indicates time-trends of the different types of degradation, which can give an early indication of a problem and aid inspection. Figure

4-8 and Figure 4-10 validate the accuracy of LEDT intelligence by indicating the fault gas zones and the visible status of generated incipient fault in the oil filled transformer.

The root cause of the failure was thermal fault caused by high resistance of the loose connection of the current collector from the tap-changer selector switch.

4.2 Case Study B: 275/88/22kV: 160 MVA, YOM: 1997

4.2.1 Background and Root Cause Analysis

This transformer was manufactured in 1997 and installed at Camden HV yard substation in 2000. In January 2001 it failed from the transmission network, and it was moved to Rotek engineering for repairs. In November 2012 one transformer failed at Makalu substation and this transformer was moved to Makalu for replacement.

The transformer was commissioned in May 2013 at the Makalu substation. The first commissioning oil samples were taken in June 2013 and the results indicated no faults being present. From January 2014 – January 2017 the online gas analyser indicated the start and escalation of carbon monoxide and other combustible gases. The transformer was under close surveillance till February 2018 where the transformer was taken out of service for inspection.

In-tank investigation revealed overheating on the tap changer changeover connection which was then repaired. The transformer was put back to service in January 2019, however, a minor increase of carbon monoxide was observed. The transformer is still in service but kept under close monitoring conditions.

The following sections discuss the indications given by the DGA data and leads to an assessment of the results relative to the root cause analysis.

4.2.2 Case Study B - Combustible Gas Trend

Figure 4-14 provides a combustible gas trend of the dissolved gas results over the period when the transformer started operating on the network. The gas trend showed all intervention points when the transformer was on the outage and when the fault gases started to increase.

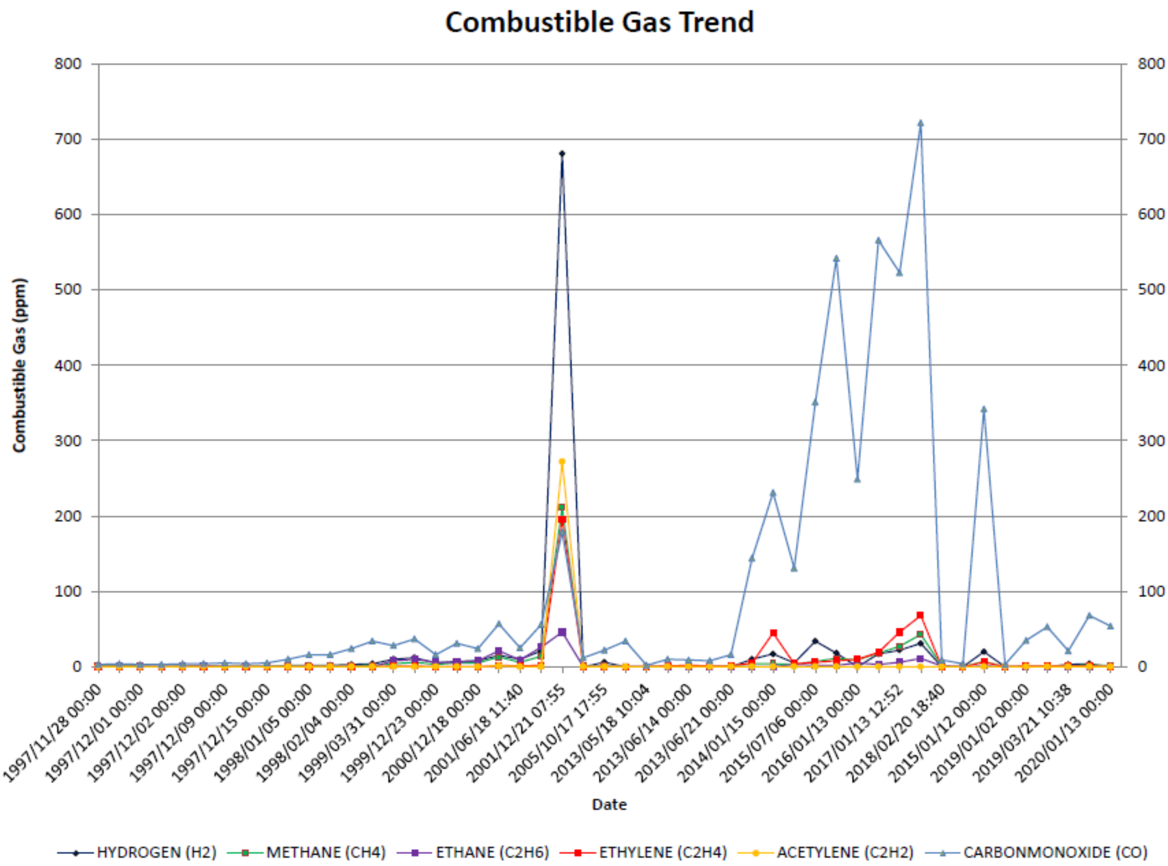


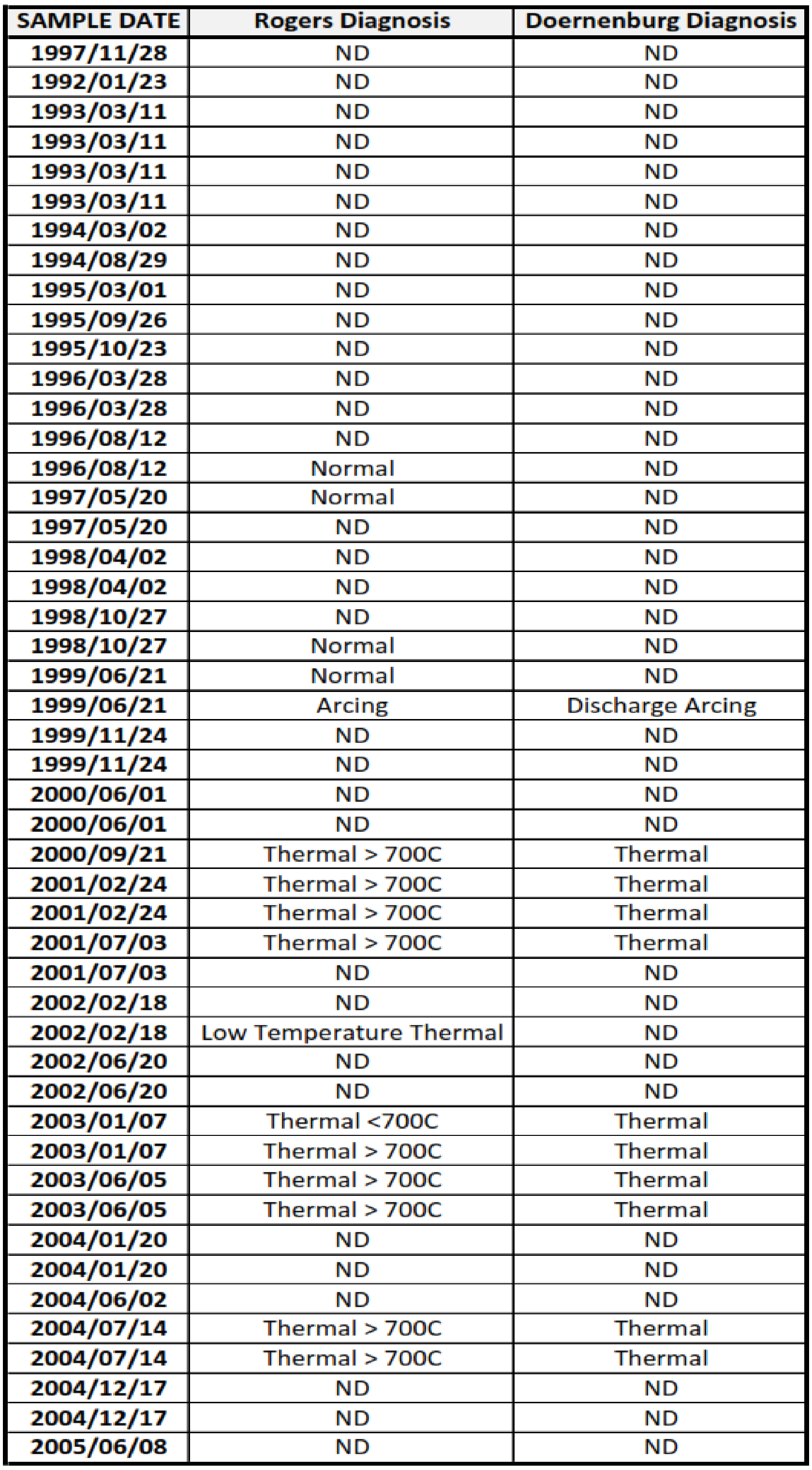
Figure 4-14: Case Study B - Combustible Gas Trend

In 2018 the transformer was taken out from service to fix the contacts and the problem was not perfectly corrected because in 2019 again the transformer indicated the increase in carbon- monoxide again. The carbon-monoxide was a clear indication of the liquid insulation degradation.

4.2.1 Case Study B - Rogers and Doernenburg Ratio Methods

Roger's and Doernenburg ratios were taken for the full sample range as indicated in Table 4-2. ND represents no diagnosis where Roger's method had 67% and Doernenburg method had 77% ND diagnosis. The dynamic pattern of selected ratios of gases can indicate the existence of degradation and to some extent, its relative rate; so, limit values and simple and complex ratios have been proposed to assist the interpretation of the DGA measurements [Wang 2007].

Table 4-2: Case Study B - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
1997/11/28	ND	ND
1992/01/23	ND	ND
1993/03/11	ND	ND
1993/03/11	ND	ND
1993/03/11	ND	ND
1993/03/11	ND	ND
1994/03/02	ND	ND
1994/08/29	ND	ND
1995/03/01	ND	ND
1995/09/26	ND	ND
1995/10/23	ND	ND
1996/03/28	ND	ND
1996/03/28	ND	ND
1996/08/12	ND	ND
1996/08/12	Normal	ND
1997/05/20	Normal	ND
1997/05/20	ND	ND
1998/04/02	ND	ND
1998/04/02	ND	ND
1998/10/27	ND	ND
1998/10/27	Normal	ND
1999/06/21	Normal	ND
1999/06/21	Arcing	Discharge Arcing
1999/11/24	ND	ND
1999/11/24	ND	ND
2000/06/01	ND	ND
2000/06/01	ND	ND
2000/09/21	Thermal > 700C	Thermal
2001/02/24	Thermal > 700C	Thermal
2001/02/24	Thermal > 700C	Thermal
2001/07/03	Thermal > 700C	Thermal
2001/07/03	ND	ND
2002/02/18	ND	ND
2002/02/18	Low Temperature Thermal	ND
2002/06/20	ND	ND
2002/06/20	ND	ND
2003/01/07	Thermal <700C	Thermal
2003/01/07	Thermal > 700C	Thermal
2003/06/05	Thermal > 700C	Thermal
2003/06/05	Thermal > 700C	Thermal
2004/01/20	ND	ND
2004/01/20	ND	ND
2004/06/02	ND	ND
2004/07/14	Thermal > 700C	Thermal
2004/07/14	Thermal > 700C	Thermal
2004/12/17	ND	ND
2004/12/17	ND	ND
2005/06/08	ND	ND

4.2.2 Case Study B - Duval’s Triangle 1

Figure 4-15 provides the Duval’s Triangle 1 for Period 1 where it is observed that the fault gas escalated from D2 high energy discharge zone to the PD and T1 region.

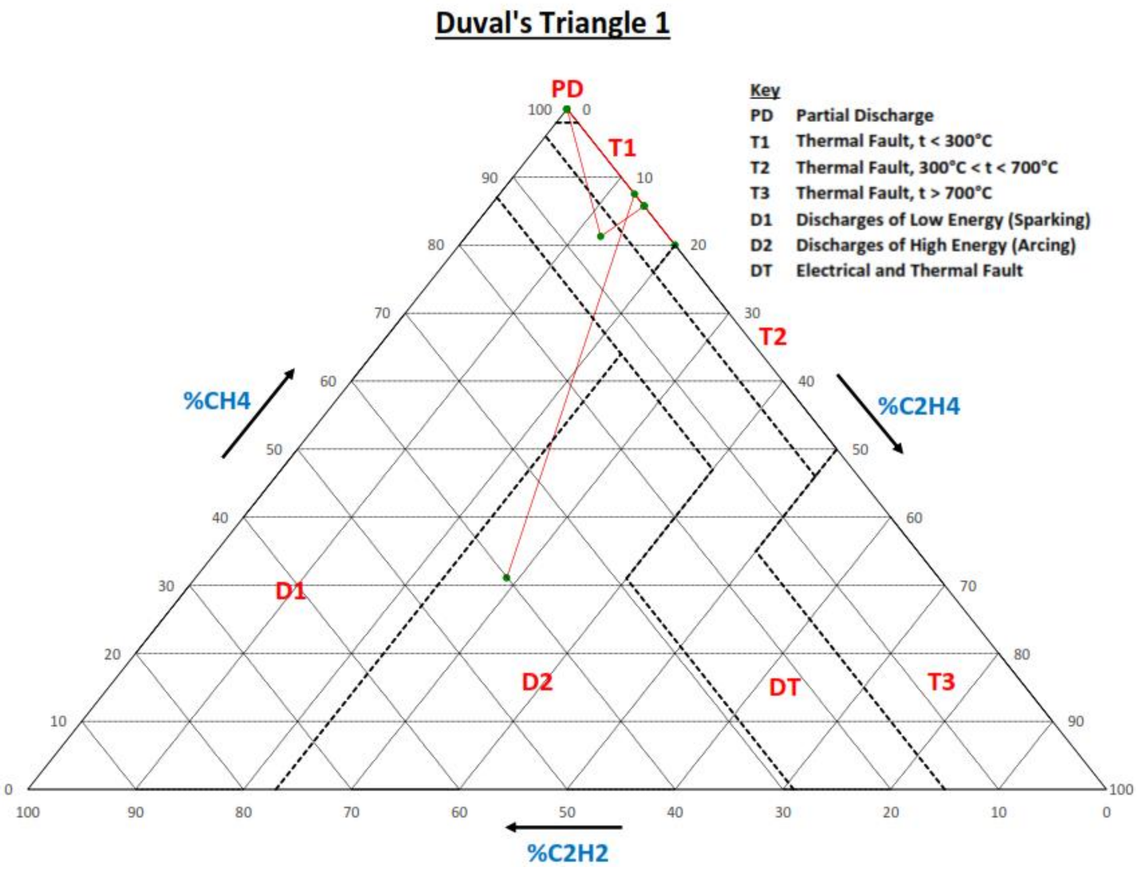


Figure 4-15: Case Study B - Duval’s Triangle 1 - Period 1

Period 2 is reflected in Figure 4-16 with samples taken after the transformer was returned to service and the fault was repaired, however, it seems like the fault was not adequately resolved because fault gases appeared on PD zone to T3 fault zone.

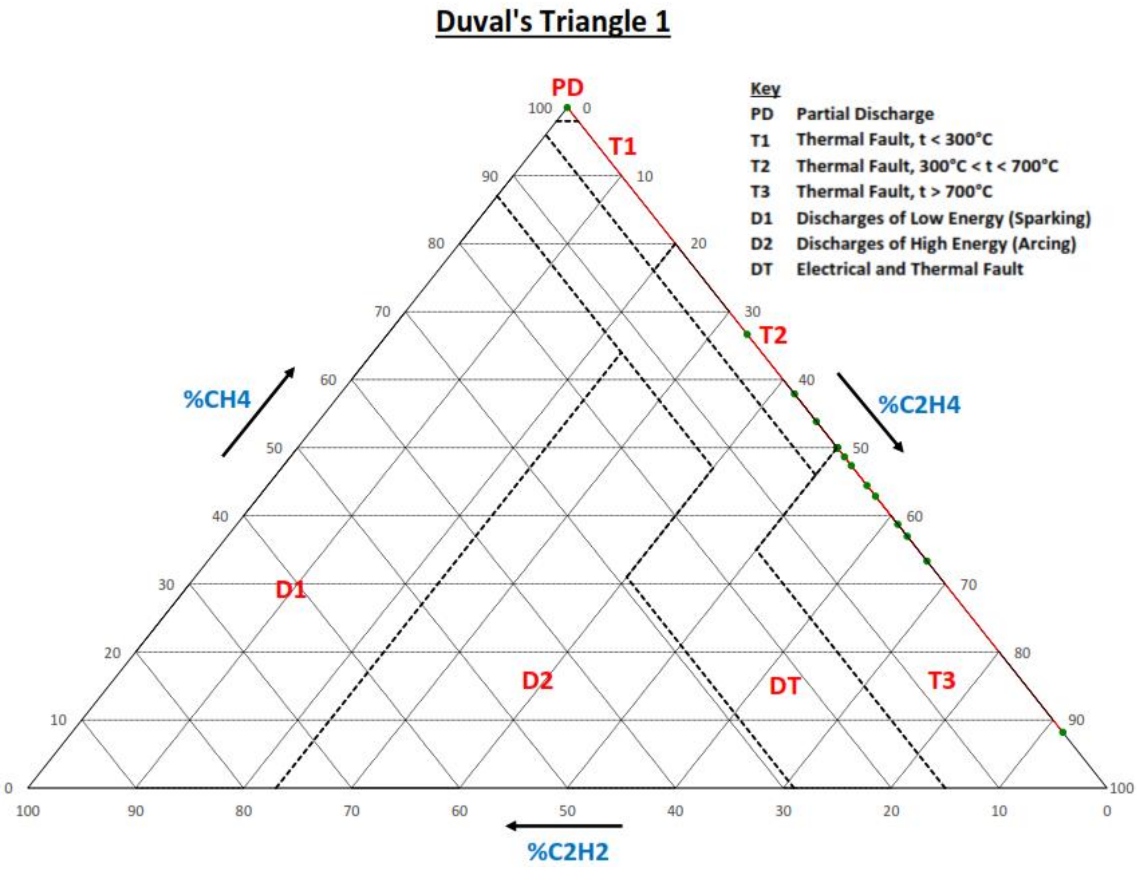


Figure 4-16: Case Study B - Duval’s Triangle 1 - Period 2

4.2.3 Case Study B - Duval’s Pentagon Method 1

The Duval’s pentagons in this case study, in Figure 4-17, indicated that this transformer has a T1 overheating problem. Duval’s Triangle 1 and Duval’s Pentagon 1 complement each other on the diagnoses results for this case study.

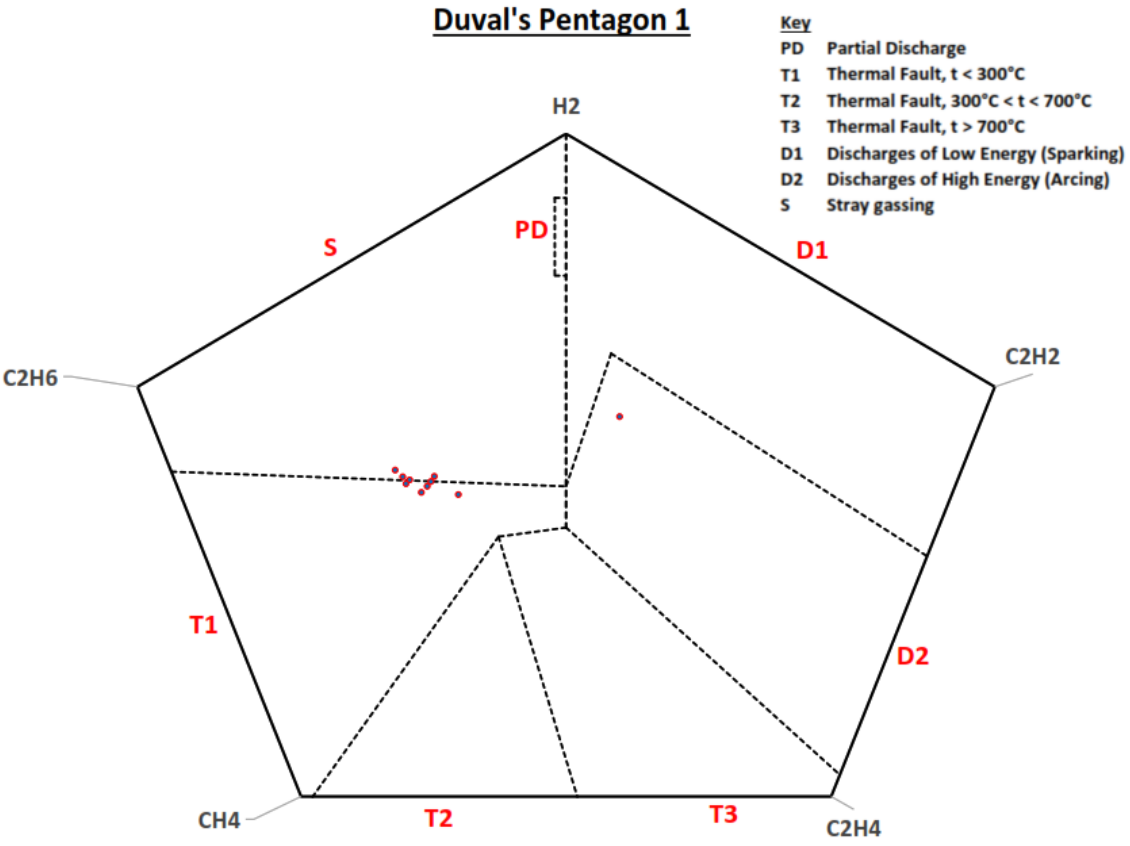


Figure 4-17: Case Study B - Duval’s Pentagon 1- Period 1

Figure 4-18 is the Duval’s Pentagon 1 for period 2. This indicates a progression from T1 to T3 fault where the fault is greater than > 700˚C. It is also identified that the Duval’s Triangle 1 and Duval’s Pentagon 1 complement each other on the diagnoses results for this case study.

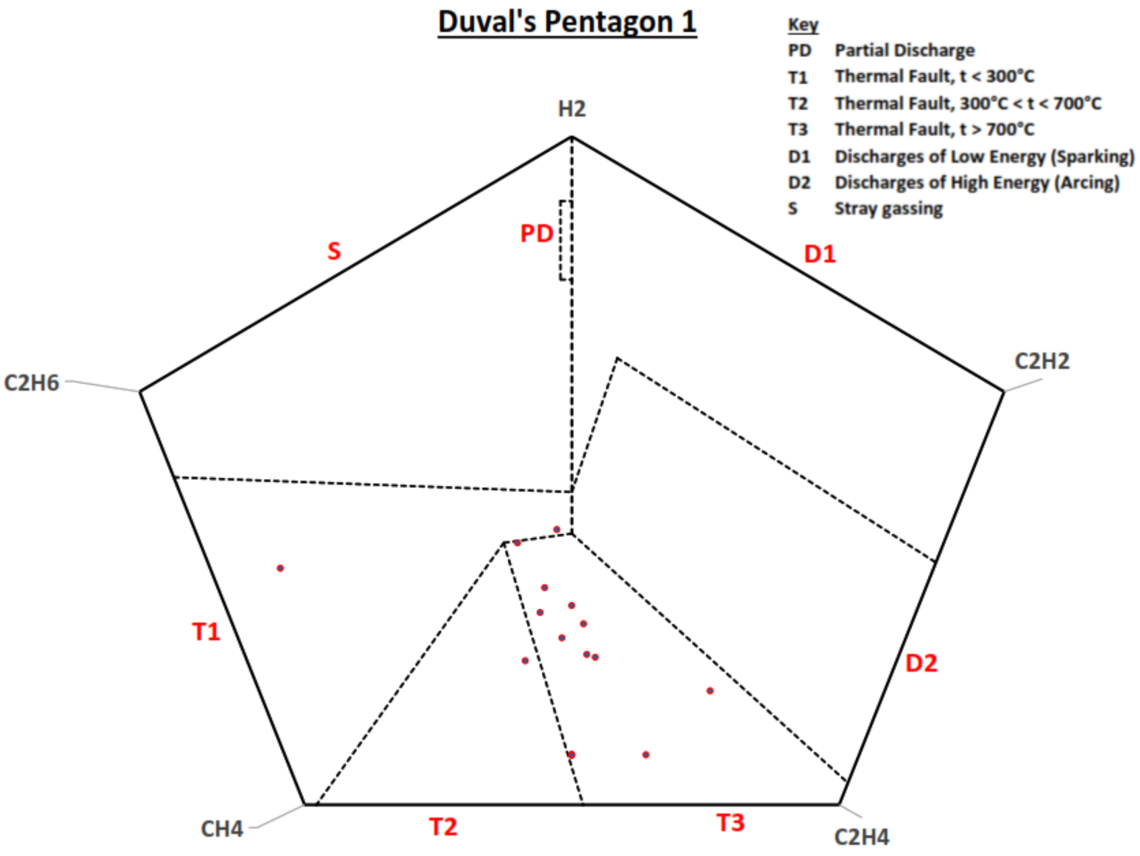


Figure 4-18: Case Study B - Duval's Pentagon 1- Period 2

4.2.4 Case Study B - LEDT and R-Value Trend

The LEDT method is a new method that was applied to generator transformers in South Africa and this method has been extended to the MEDT model which identified the insulation degradation based on medium energy dissolved gases.

The LEDT will be compiled for two periods. Period 1 LEDT as depicted in Figure 4-19 and the R-value in Figure 4-20 is immediately after 28 November 1997 where the combustible gases were stable until the dissolved gases escalated out from the normal range. Period 2 LEDT as depicted in Figure 4-21 and R-value in Figure 4-22 is when the transformer was then returned to service on the 21 December 2001.

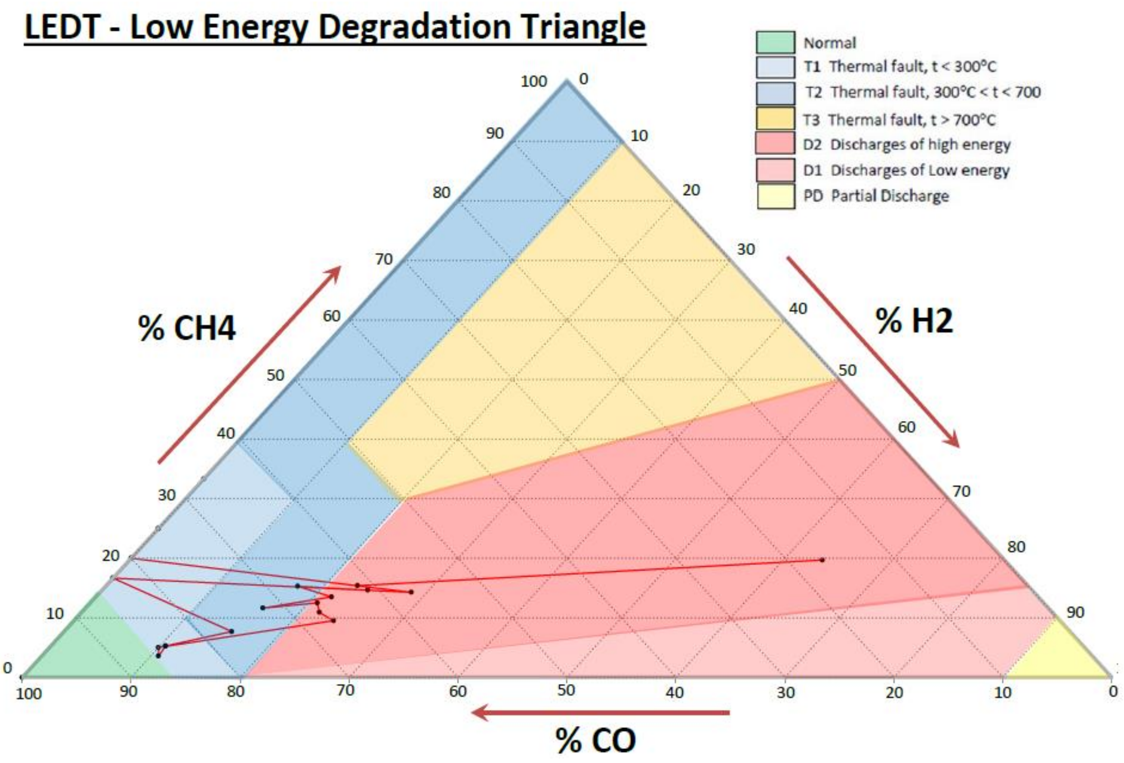


Figure 4-19: Case Study B - LEDT Period 1

LEDT Period 1 indicated thermal faults started at low thermal fault T1 and escalated to medium thermal fault T2 with the transition of thermal/electrical discharges D2 zone. The R-Value trend complemented this diagnosis results with time escalation of this period until the transformer was taken out of service.

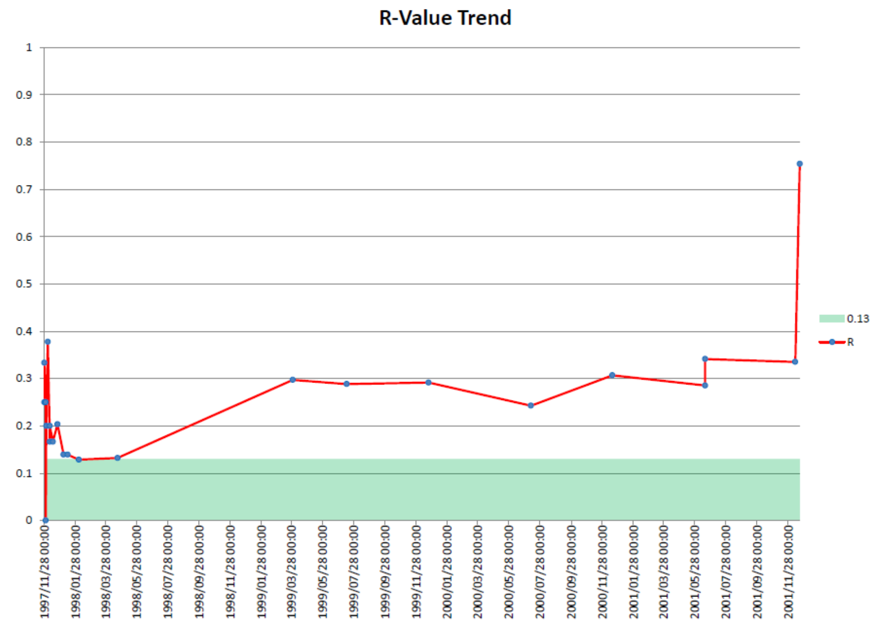


Figure 4-20: Case Study B - R-Value - Period 1

The LEDT for Period 2 although mostly in the green region indicated some movement towards the abnormal regions of thermal T1 and discharges D2. This provides some evidence that although the transformer was repair there was still a problem present.

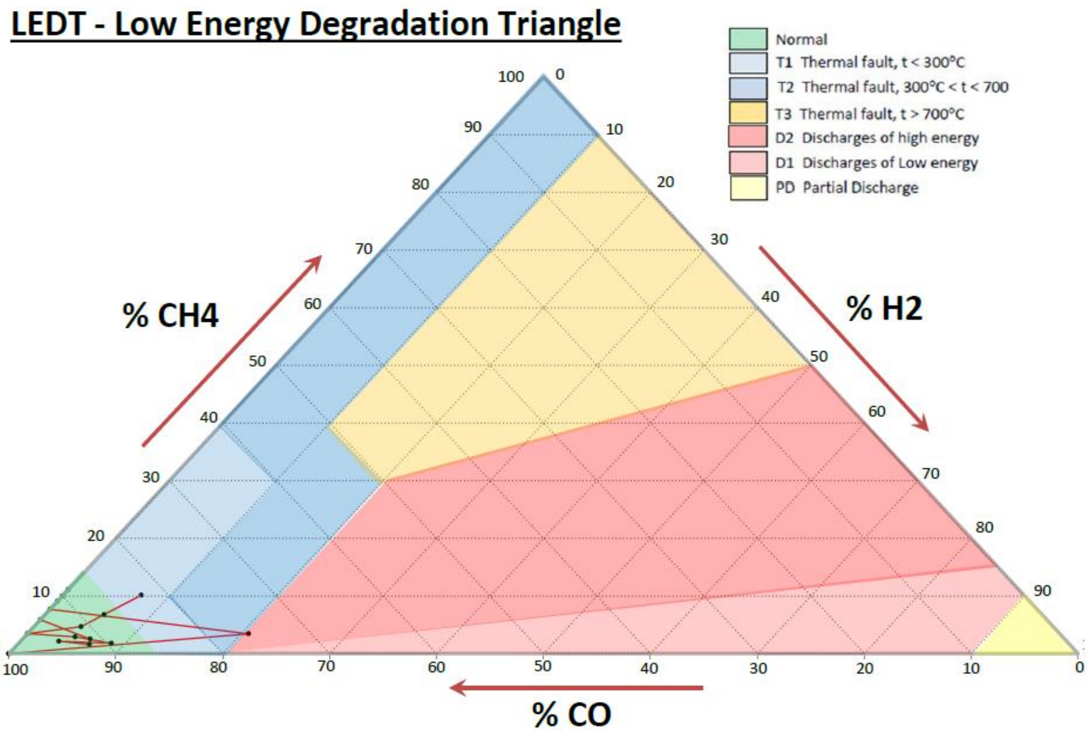


Figure 4-21: Case Study B - LEDT - Period 2

This is also evident in the R-value trend where there is an increasing trend out from the normal region.

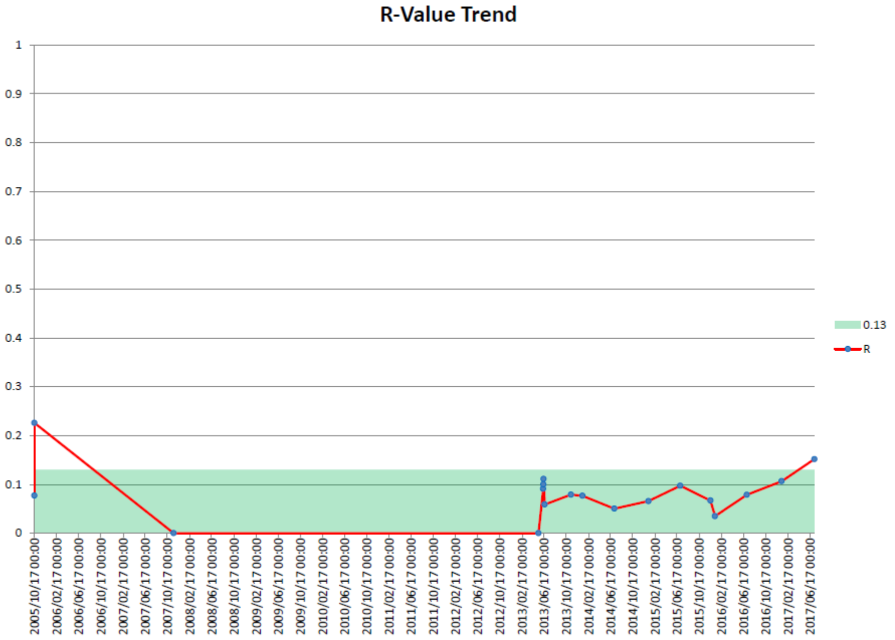
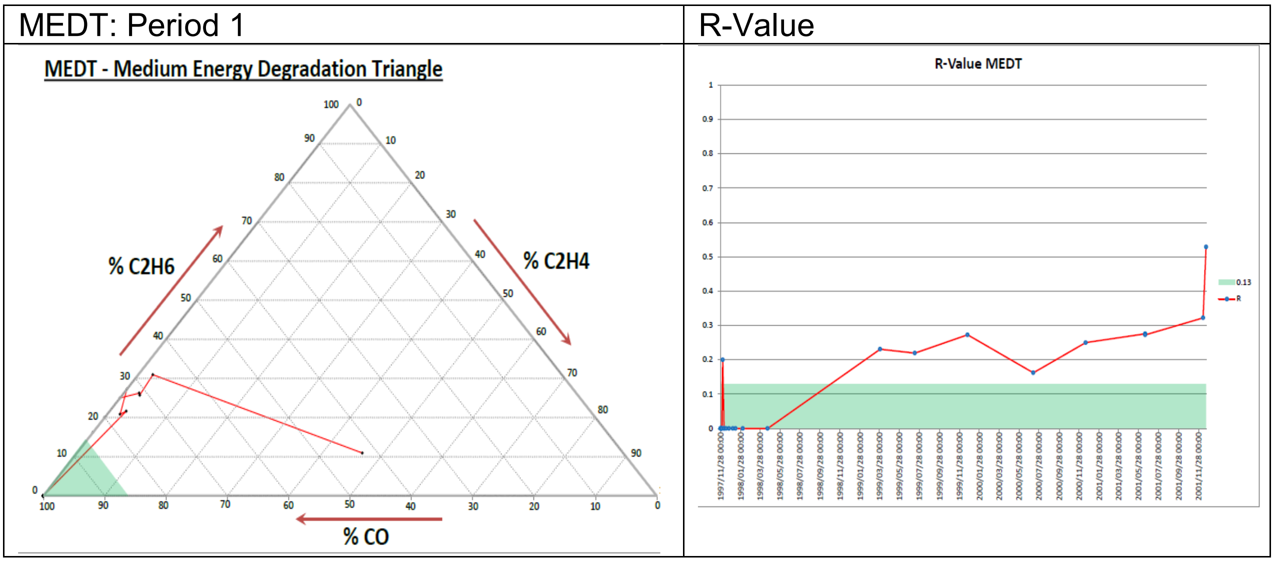


Figure 4-22: Case Study B - R-Value - Period 2

4.2.5 Case Study B - Extension to MEDT

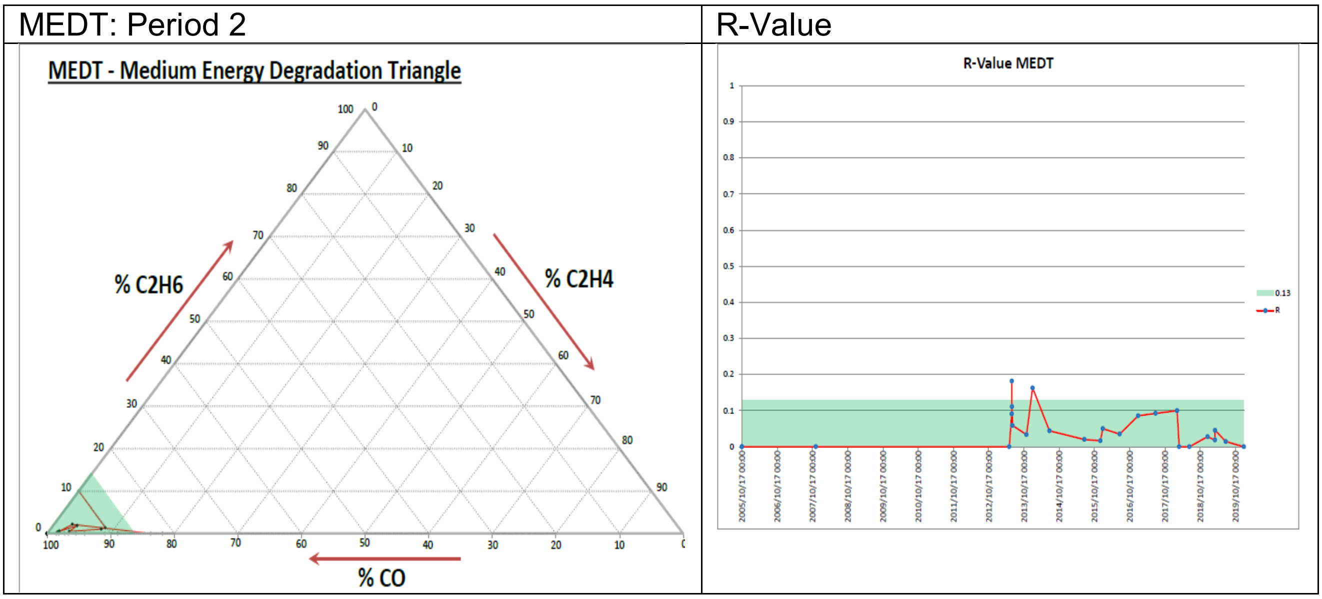
The MEDT: Period 1 (Figure 4-23) indicates an increasing trend out of the normal region which is supported by the R-value trend.


MEDT: Period 1

R-Value

Figure 4-23: Case Study B - MEDT and R-Value - Period 1

The MEDT for Period 2 (Figure 4-24) also indicated some activity within the normal region with an increasing trend indicating medium energy discharges or heating.is the perfect complement to the LEDT method in terms of showing the fault direction in the transformer.


MEDT: Period 2

R-Value

Figure 4-24: Case Study B - MEDT and R-Value - Period 2

4.2.6 Case Study B: Evaluation

The internal inspection on the transformer indicated signs of overheating on the connection of the current collector on the tap-changer for the blue-phase selector switch and no lock nut was observed on the bolt, which caused the problem of high resistance. See the damaged component in Figure 4-25.

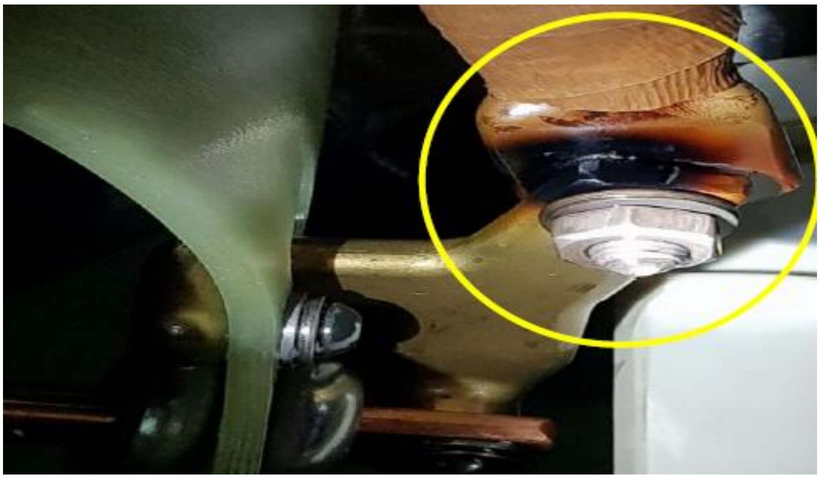


Figure 4-25: Overheating on changeover connection

In September 2017 after the completion of the outage, the electrical tests were performed, and DC winding test result showed the deviations on tap positions 5 & 13 in the blue phase. The measurement results for the blue phase at tap 5 &13 have higher resistance than other phases that caused current circulation. DC winding test was repeated after completion after the transformer repairs to confirm that the problem was corrected, All measurement results showed no obvious deviations.

In this case study, the Roger's and Doernenburg ratios do not offer a consistent interpretation of the degradation or its trend. The Duval's Triangle 1 and pentagon were in alignment with the LEDT and MEDT (each with R) methods in identifying the thermal fault. The Duval's Triangle 1 showed the fault was escalated to DT zone where the transition of thermal and electrical fault occurred, while Duval's Pentagon 1 does not had have that fault zone. Both Duval's Triangle 1 and LEDT method indicated that the fault was escalated to high energy discharge D2 zone. The LEDT and MEDT Method 1 had R-Values that indicated the inception of the fault inside the transformer and its progress before any action could be taken. The DGA interpretations were consistent with the type of fault. The root cause of the thermal fault was the overheating of connections of current collector of selector switch.

4.3 Case Study C: 400/132/22kV: 500 MVA, YOM: 1997

4.3.1 Background and Root Cause Analysis

This transformer was manufactured in 1997 and 2001 moved from strategic stores to the transmission substation for installation on the Northern Grid. The transformer was loaded at no more than 50% of the MVA rating according to the transmission strategy of N-1 capacity.

The first commissioning oil samples were taken in December 2001 and the results indicated no faults until November 2003, when combustible gases started escalating. In December 2006, the online gas analyser identified further escalation of dissolved gases. In May 2009, the transformer was on outage for tap-changer maintenance and further increases for combustible gases were observed.

The transformer tripped from service in June 2010 on a pressure relief valve (PRV) due to the connected breaker failure. An on-site internal inspection was carried out and no effects of the trip could be observed. In May 2012 a modification was done on the tap changer as per the manufacturer instruction.

In November 2012, this transformer was derated from 500MVA to supply 304MVA to the network. On the day of failure in November 2015, the transformer was in service supplying 203 MVA on the transmission network and caught fire.

The transformer had an oil type online tap changer without a selector and diverter compartment, so the selector was open/connected to the main tank. The transformer was equipped with a gas analyser connected at the bottom of the main tank valve. When the gases were increasing the load was reduced. Oil samples were taken to confirm the gas analyser, but the transformer failed before further action could be taken.

4.3.2 Case Study C - Combustible Gas Trend

Figure 4-26 provides a combustible gas trend of the dissolved gas results over the period. Since this transformer was first installed in 2001, the combustible gases were normal and showed a gradual increase especially ethylene and carbon monoxide and these two gases ethylene and carbon monoxide were clear indication of degradation for solid and liquid insulation. However, the acetylene was low there were no arcing or partial discharges developing. From 2006 all dissolved gases were escalating till the transformer was taken out from service on 21 June 2010.

The transformer was put back into service in 2012 where the combustible gases started increasing again but at the acceptable level except for carbon monoxide which continued escalating. The combustible gases were fluctuating due to the reduced loading (304MVA) of the transformer up until the transformer failed on the 15 November 2015.

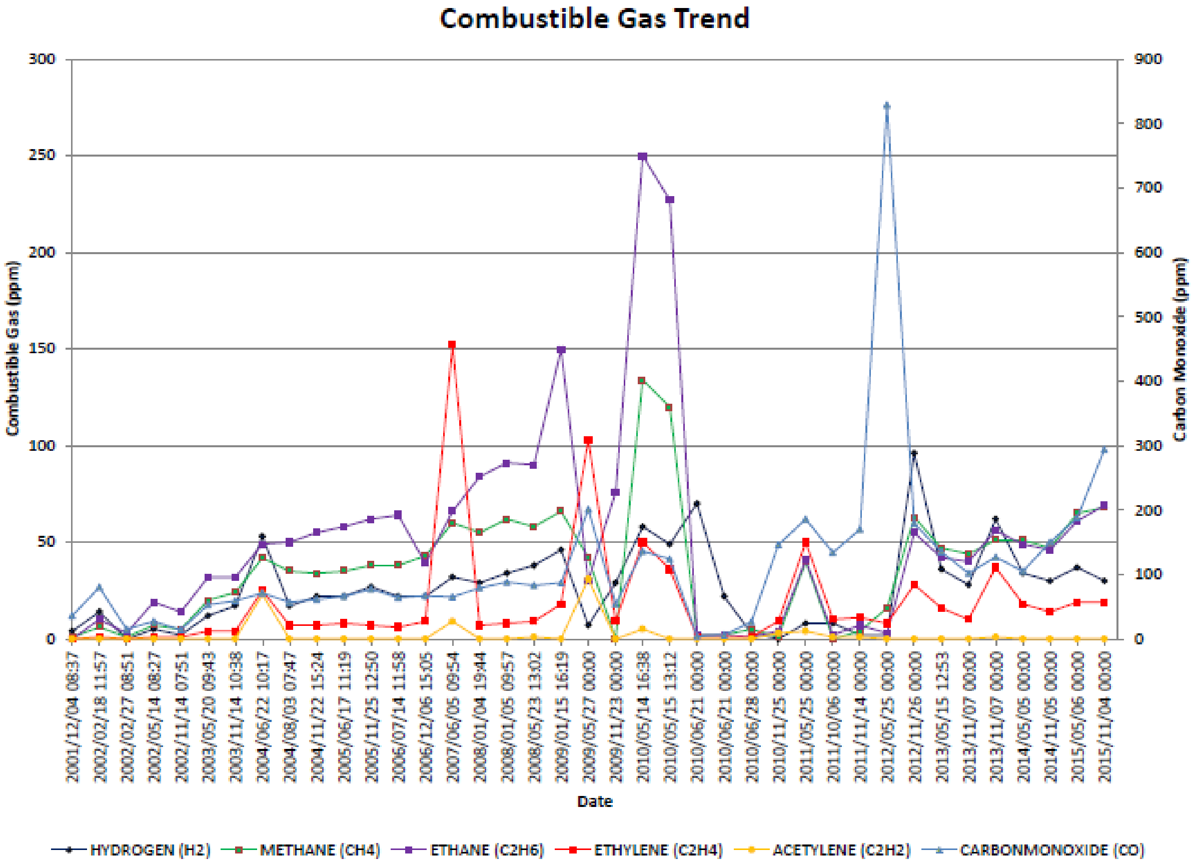
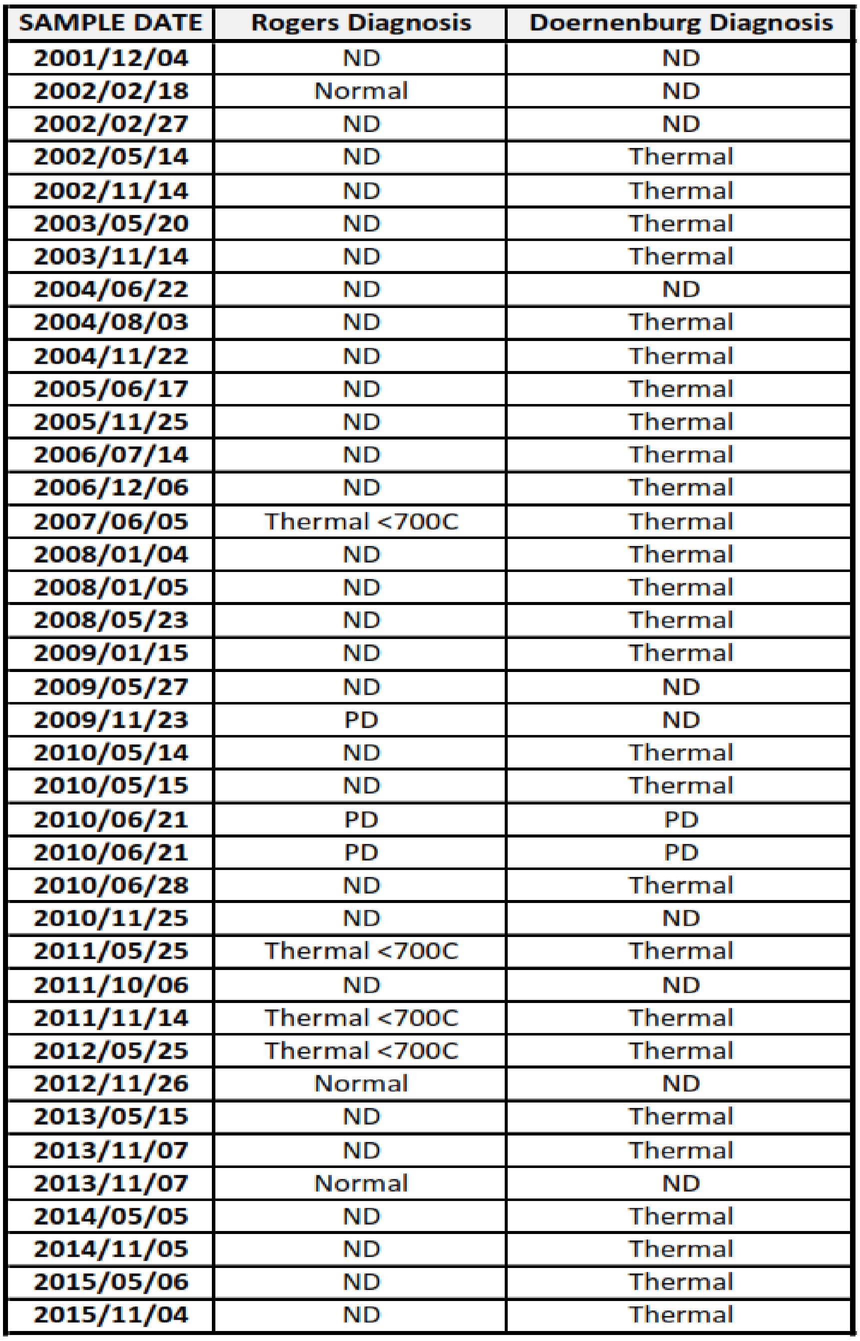


Figure 4-26: Case Study C - Combustible Gas Trend

4.3.3 Case Study C - Rogers and Doernenburg Ratio Methods

Roger's and Doernenburg ratios were taken for the full sample range as indicated in Table 4-3 below. ND represents no diagnosis where Rogers method had 74% and Doernenburg method had 26% ND diagnosis. It is observed that Roger's ratio had only one diagnosis of "thermal > 700°C". Doernenburg ratio had a diagnosis of "PD" and "Thermal".

Table 4-3: Case Study C - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
2001/12/04	ND	ND
2002/02/18	Normal	ND
2002/02/27	ND	ND
2002/05/14	ND	Thermal
2002/11/14	ND	Thermal
2003/05/20	ND	Thermal
2003/11/14	ND	Thermal
2004/06/22	ND	ND
2004/08/03	ND	Thermal
2004/11/22	ND	Thermal
2005/06/17	ND	Thermal
2005/11/25	ND	Thermal
2006/07/14	ND	Thermal
2006/12/06	ND	Thermal
2007/06/05	Thermal <700C	Thermal
2008/01/04	ND	Thermal
2008/01/05	ND	Thermal
2008/05/23	ND	Thermal
2009/01/15	ND	Thermal
2009/05/27	ND	ND
2009/11/23	PD	ND
2010/05/14	ND	Thermal
2010/05/15	ND	Thermal
2010/06/21	PD	PD
2010/06/21	PD	PD
2010/06/28	ND	Thermal
2010/11/25	ND	ND
2011/05/25	Thermal <700C	Thermal
2011/10/06	ND	ND
2011/11/14	Thermal <700C	Thermal
2012/05/25	Thermal <700C	Thermal
2012/11/26	Normal	ND
2013/05/15	ND	Thermal
2013/11/07	ND	Thermal
2013/11/07	Normal	ND
2014/05/05	ND	Thermal
2014/11/05	ND	Thermal
2015/05/06	ND	Thermal
2015/11/04	ND	Thermal

4.3.4 Case Study C - Duval’s Triangle 1 Method

Duval’s Triangle 1 method on Period 1 (Figure 4-27) indicated that the fault started by discharging at low temperatures. The combustible gases then moved towards T3 which is a thermal fault greater than 700°C meaning that there was severe overheating in the transformer.

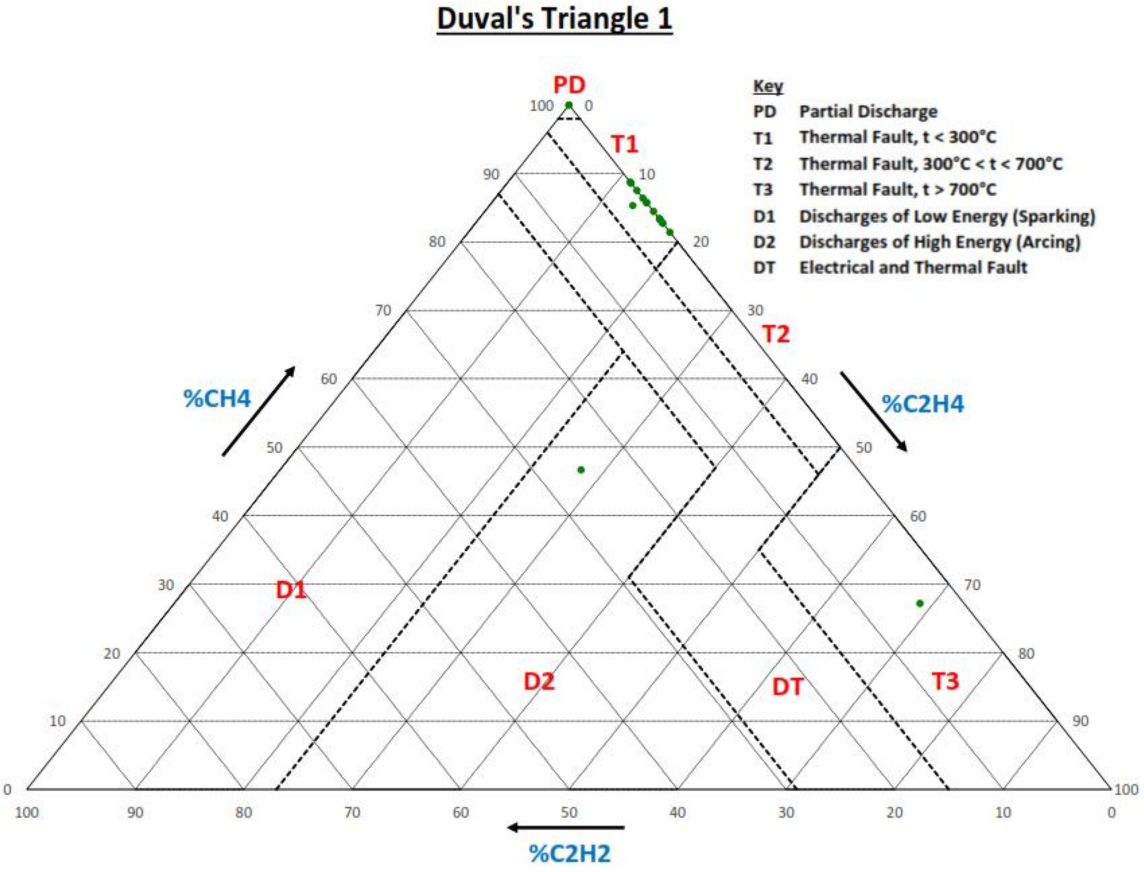


Figure 4-27: Case Study C - Duval’s Triangle 1 - Period 1

In Period 2 (Figure 4-28), Duval’s Triangle 1 indicated that the combustible gases detected fault at T2 and escalated to T3. Duval’s Triangle 1 showed the fault escalated to DT zone where the transition of thermal and electrical fault occurred and on DT zone where the transition fault caused the transformer failure.

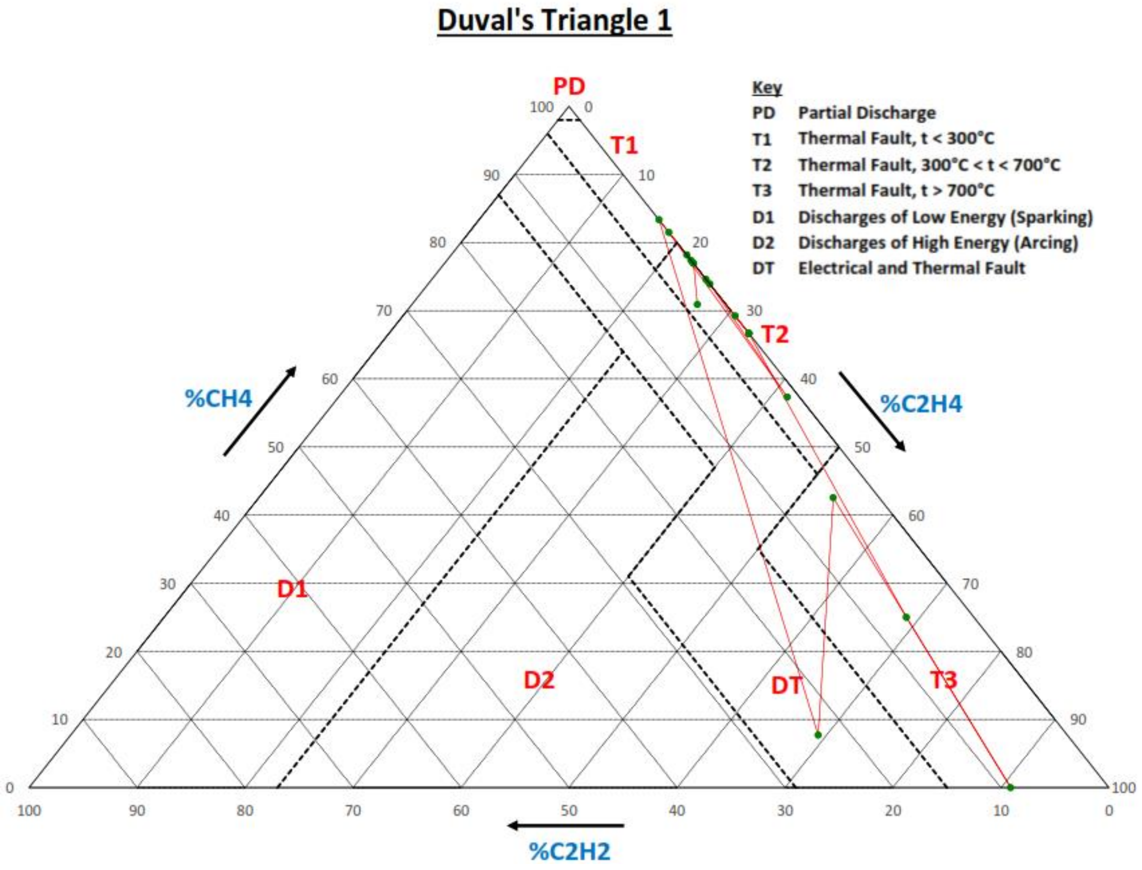


Figure 4-28: Case Study C - Duval's Triangle 1 - Period 2

4.3.5 Duval's Pentagon 1 Method

This method (Figure 4-29) detected the fault gases from low temperature mainly in the T1 region. The diagnose results were similar with the fault result from Duval's Triangle 1 except Duval's Pentagon 1 does not have DT zone where it showed the mixture of two different types of which was thermal and electrical fault.

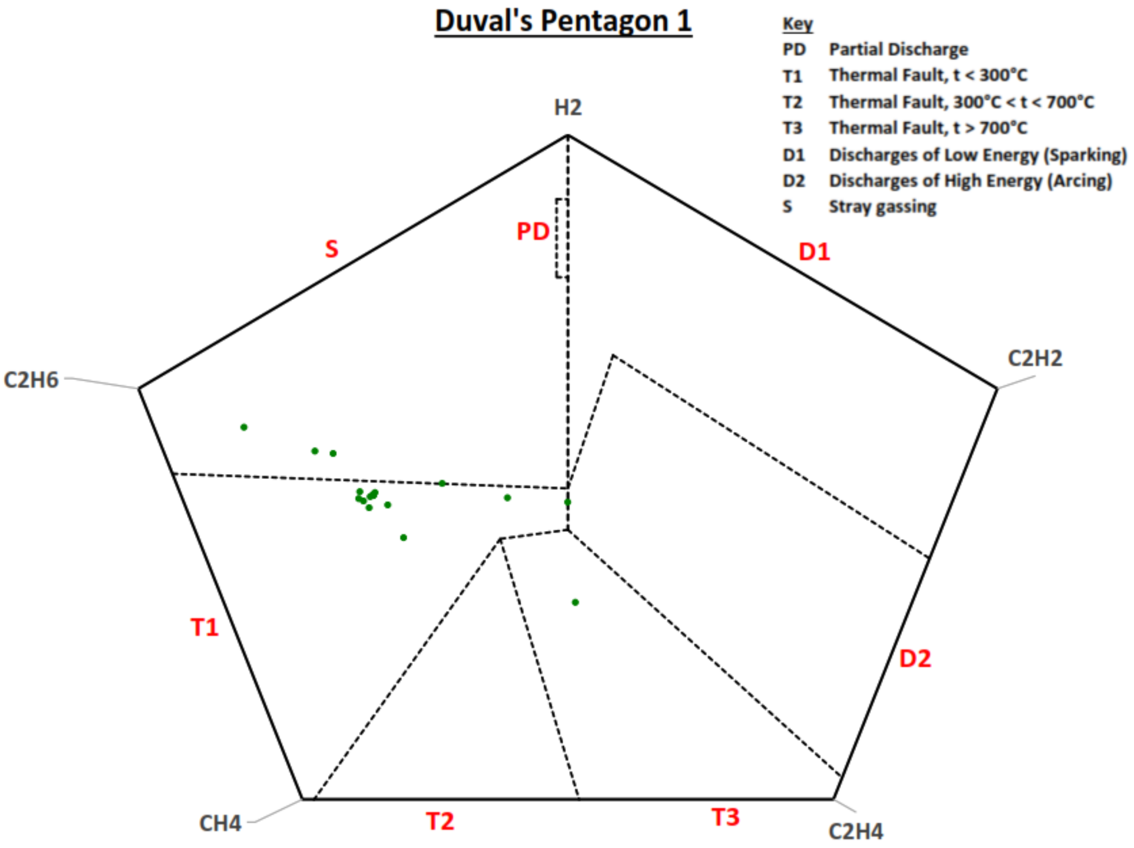


Figure 4-29: Case Study C - Duval's Pentagon 1 - Period 1

Period 2 (Figure 4-30) indicates the fault in the T1 region and progression to the T2 and T3 regions. The diagnose results were similar with the fault result from Duval's Triangle 1 except Duval's Pentagon 1 does not have DT zone where it showed the mixture of two different types of which was thermal and electrical fault.

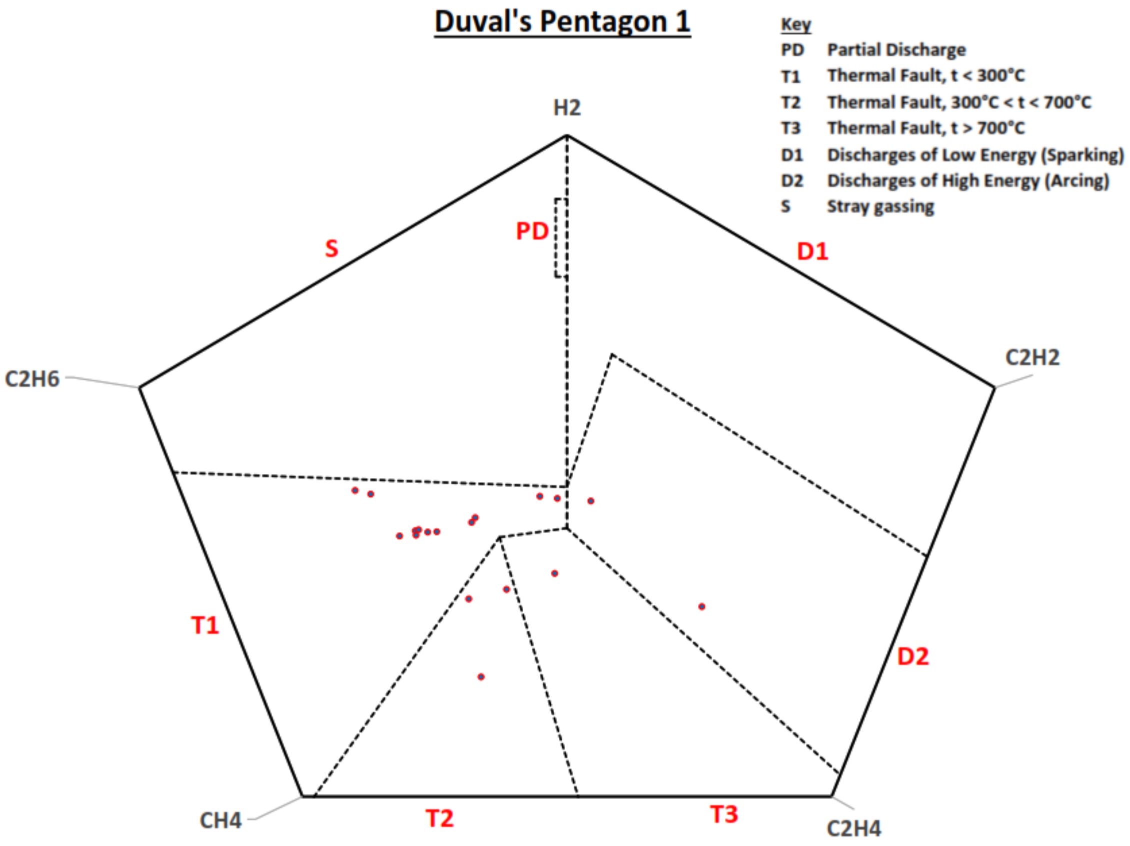


Figure 4-30: Case Study C - Duval's Pentagon 1 - Period 2

4.3.6 Case Study C - LEDT and R-Value Trend

The LEDT will be presented for two periods, before and after it was inspected in June 2010.

The LEDT during Period 1 (Figure 4-31) indicated that the transformer had a defect on the active part at commissioning because the combustible gases were constantly increasing. From the LEDT it can be seen the transformer started operating form the normal regions and then progressed to the T2 thermal fault region and after discharges in the D2 region it finally settled in the T3 fault region before it was taken out of service.

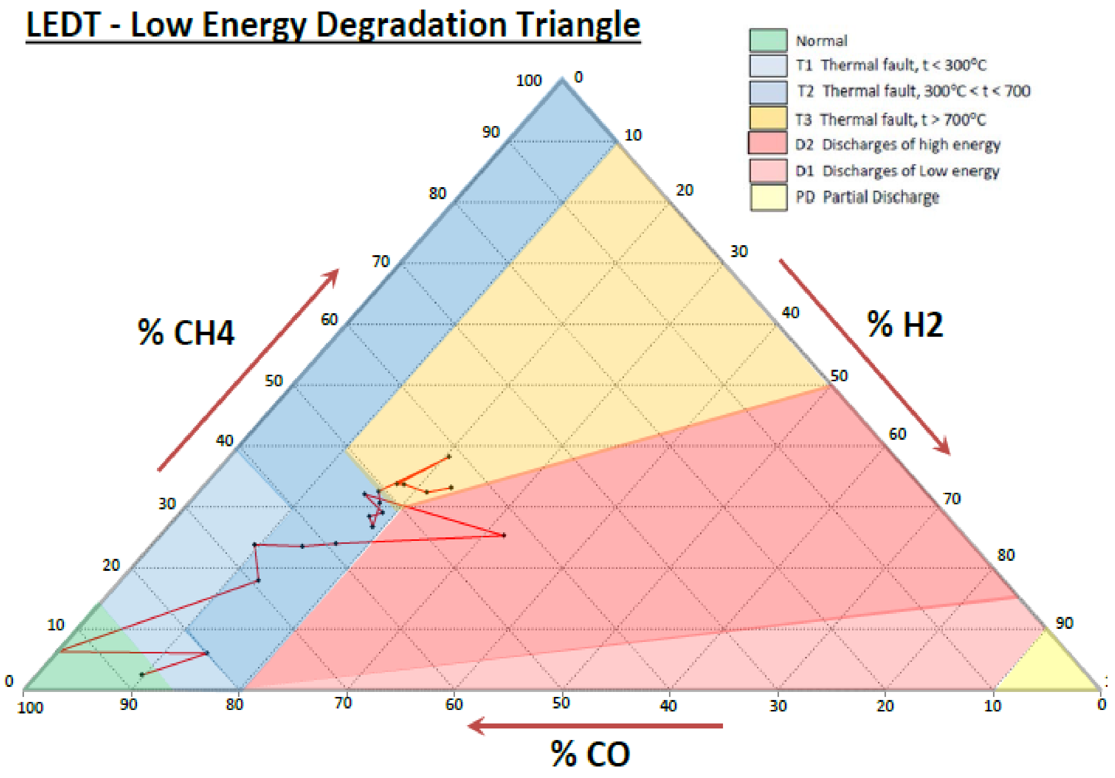


Figure 4-31: Case Study C - LEDT - Period 1

The R-value trend for Period 1 (Figure 4-32) indicated that the incipient fault started from the normal region and showed the combustible gases moving towards the abnormal region. R-Value trend complemented the diagnostic results observed on LEDT Period 1 and that the fault was progressing.

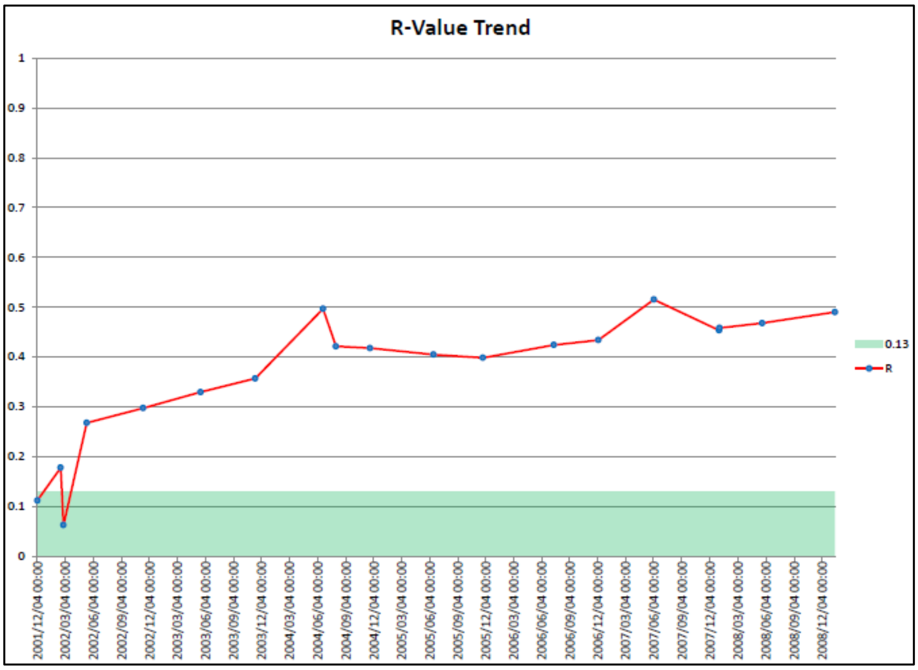


Figure 4-32: Case Study C - R-Value - Period 1

In Period 2, the in-tank investigation was undertaken, and a defect was observed. This was repaired and the transformer was returned to service, all the combustible gases started increasing which led to the reduction of the load to 304MVA. This was confirmed with the LEDT (Figure 4-33) and R-Value (Figure 4-34) trend with the decrease of the combustible gases because the transformer was de-energized from the network for tap charger maintenance and after the repair there was an increase. This was then curtailed with the decrease in loading.

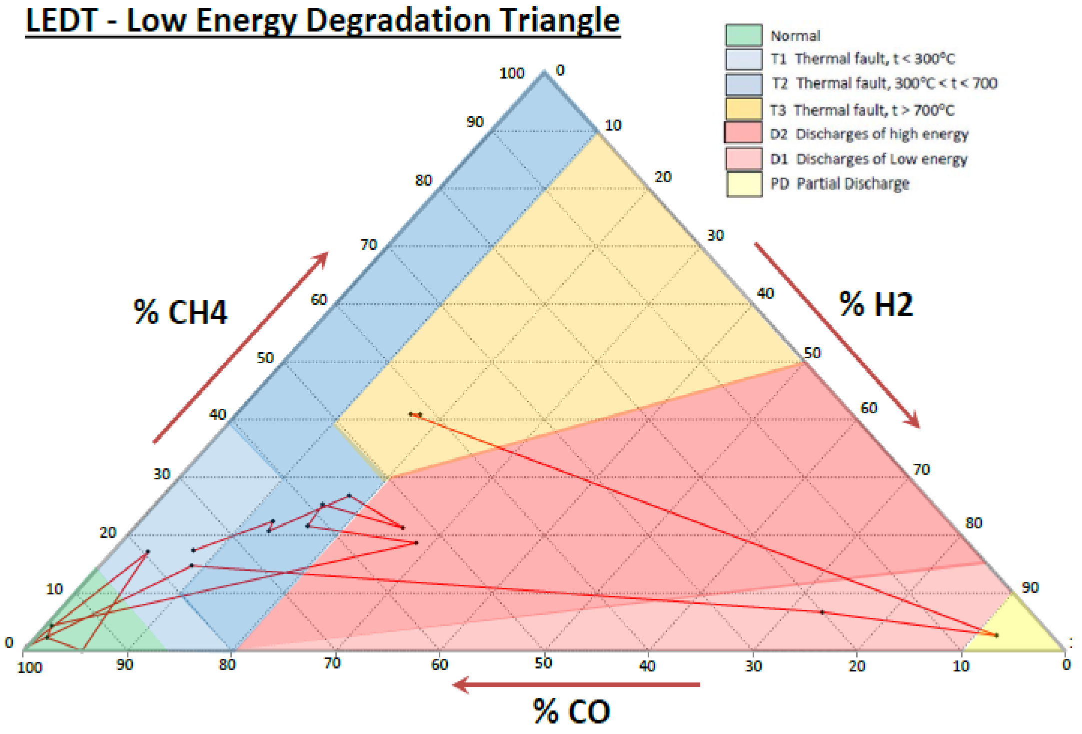


Figure 4-33: Case Study C - LEDT - Period 2

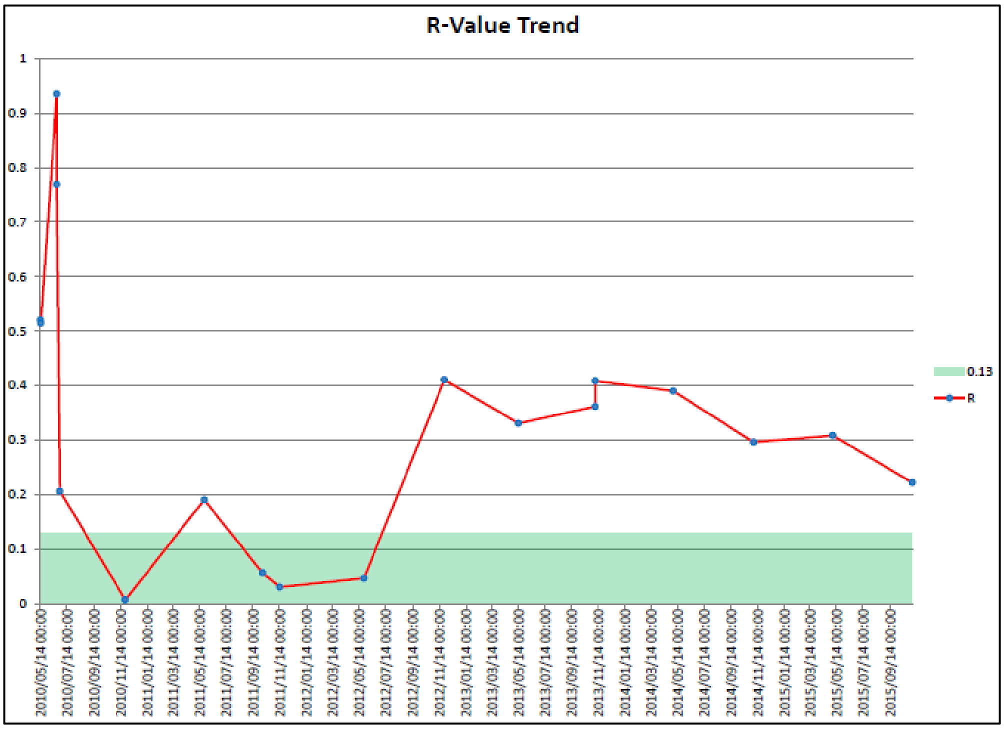


Figure 4-34: Case Study C - R-Value Period 2

4.3.7 Case Study C - Extension of MEDT

The MEDT and associated R-Value for period 1 (Figure 4-35) also showed a movement from the normal region to the abnormal region. This was in line with the diagnosis from the LEDT.

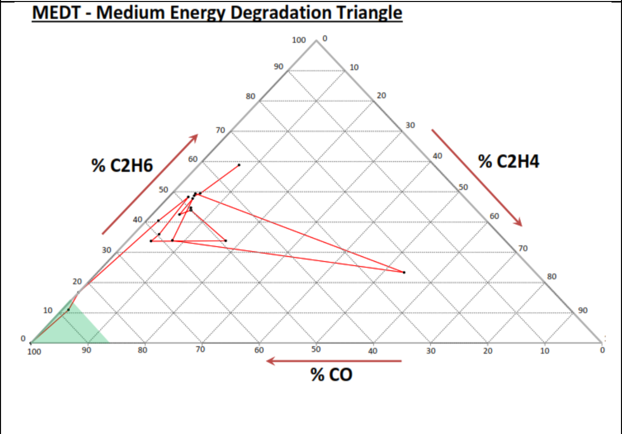
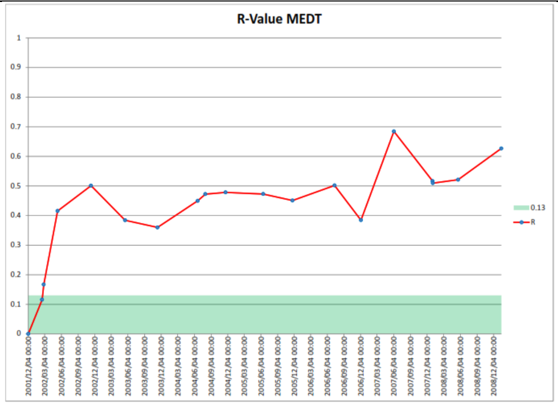
MEDT: Period 1	R-Value
	

Figure 4-35: Case Study C - LEDT and R-Value Period 1

The MEDT (Figure 4-36) for Period 2 complement the LEDT Period 2 diagnostic results with the R-value trends being very similar.

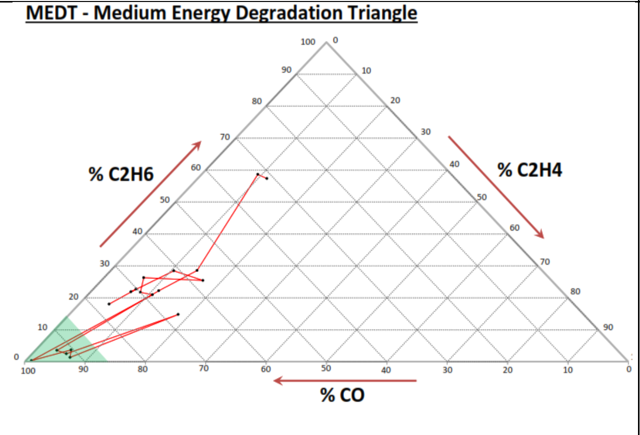
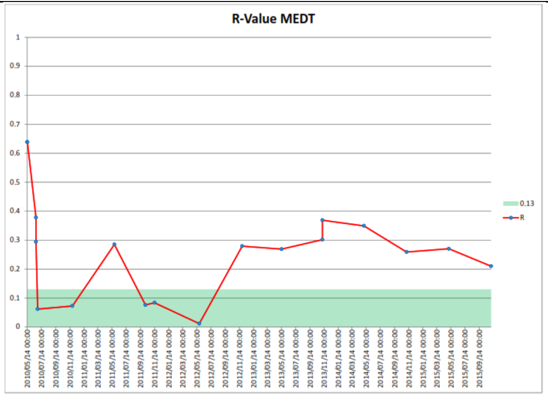
MEDT: Period 2	R-Value
	

Figure 4-36: Case Study C - MEDT and R-Value Period 2

4.3.8 Case Study C: Evaluation

An internal inspection was done after the transformer caught the fire. The findings indicated that the fault was inside in the HV bushing turret as observed in Figure 4-37. It was found that the rose was not properly connected with the oil side of the bushing connection resulting in discharges and thermal heating.

Duval's Triangle 1 analysis low thermal fault escalation to high thermal fault and DT result, which is transition zone for thermal and electrical fault. Whereas LEDT and Duval's Pentagon 1 started indication the fault gas at the normal zone and showed the escalation of fault gas to high energy discharge zone.

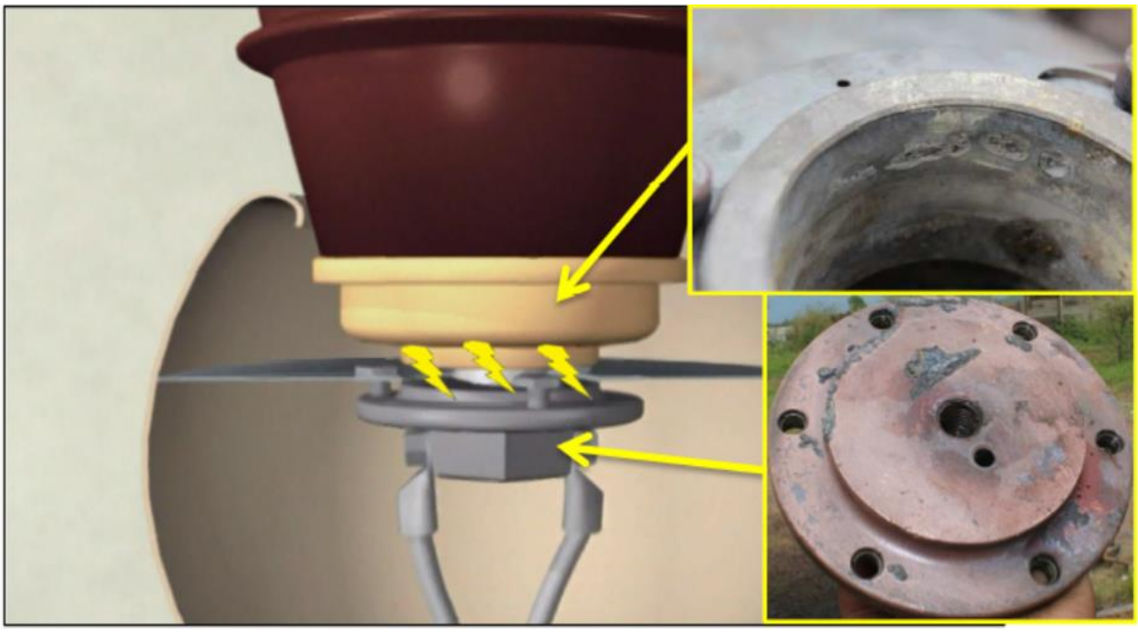


Figure 4-37: Rose improperly connected with oil side of bushing.

The root cause of the transformer failure was loose bushing rose discharge to the bushing turret because were on differential potential.

4.4 Case Study D: 132/33kV: 80 MVA. YOM: 2004

4.4.1 Background and Root Cause Analysis

This transformer was manufactured in 2004 and kept at strategic storage. In 2005 it was moved from strategic stores to the distribution network for installation. The transformer was loaded full capacity of the MVA rating.

The first oil samples were taken in January 2005 when the transformer was commissioned with the oil results indicating no abnormalities. The oil sample taken in May 2007 indicated an escalation in methane (CH_4), ethane (C_2H_6) and carbon monoxide (CO). This prevailed until March 2010, when the transformer was taken out of service. During the outage the DC winding resistance test results indicated a deviation on the white phase when compared with the other two phases. The transformer was put back to service without performing the internal inspection. When the transformer was returned to service, the same fault gases continued with increment level till the transformer failed in October 2017.

The internal investigation was arranged by the grid and an inter-turn fault was identified on the HV winding of the white phase. The transformer was scrapped on site.

4.4.2 Case Study D - Combustible Gas Trend

Figure 4-38 provides a combustible gas trend of the dissolved gas results over the period. It is observed that the ethane and carbon monoxide levels were increasing at a fast rate together with some increase in methane. The hydrogen, ethylene and acetylene levels were relatively low indicating that this initially was of a lower energy fault.

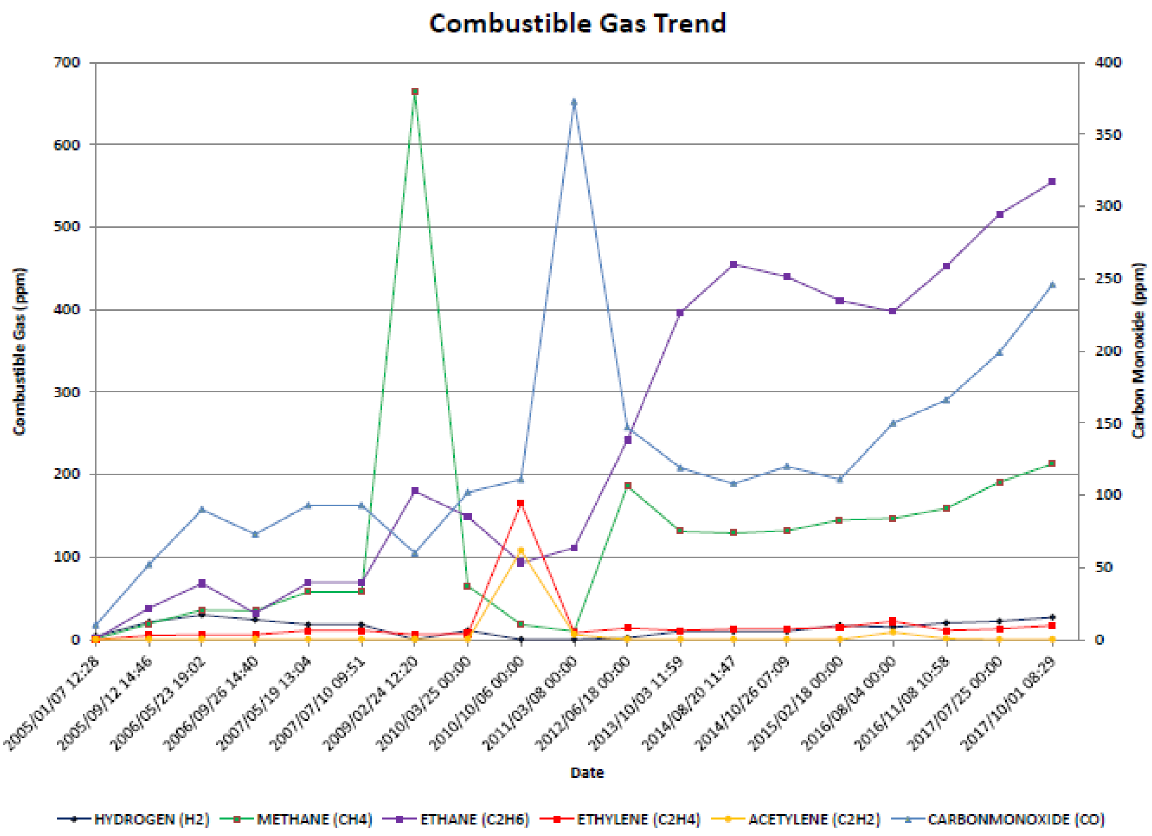
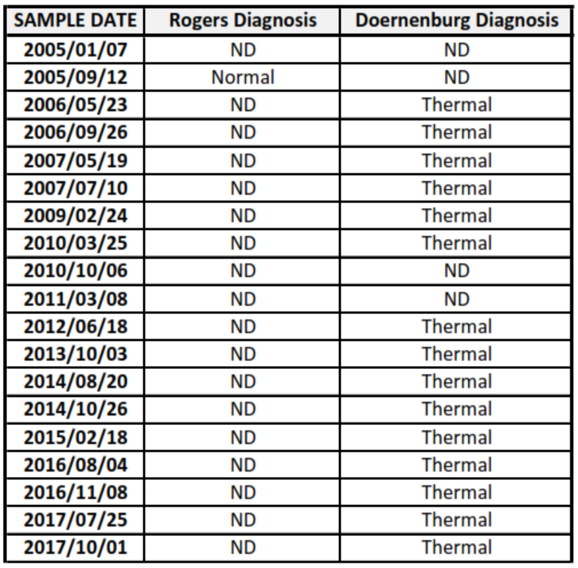


Figure 4-38: Case Study D - Combustible Gas Trend

4.4.3 Case Study D - Rogers and Doernenburg Ratio Methods

Roger’s and Doernenburg ratios were taken for the full sample range as indicated in the Table 4-4 below. ND represents no diagnosis where Roger’s Ratio method had 94% and Doernenburg method had 24% ND diagnosis. It is observed that Roger’s ratio had only one diagnosis of “thermal > 700°C”. Doernenburg ratio had a diagnosis of “PD” and “Thermal”.

Table 4-4: Case Study D - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
2005/01/07	ND	ND
2005/09/12	Normal	ND
2006/05/23	ND	Thermal
2006/09/26	ND	Thermal
2007/05/19	ND	Thermal
2007/07/10	ND	Thermal
2009/02/24	ND	Thermal
2010/03/25	ND	Thermal
2010/10/06	ND	ND
2011/03/08	ND	ND
2012/06/18	ND	Thermal
2013/10/03	ND	Thermal
2014/08/20	ND	Thermal
2014/10/26	ND	Thermal
2015/02/18	ND	Thermal
2016/08/04	ND	Thermal
2016/11/08	ND	Thermal
2017/07/25	ND	Thermal
2017/10/01	ND	Thermal

4.4.4 Case Study D - Duval’s Triangle 1 Method

The Duval’s Tringle method (Figure 4-39) for period 1 started to measure from the partial discharge region with progression into the T2 region. In period 2, it is clearly shown that the fault gases were increasing from T1 which is the thermal fault less than 300° C to D2 which is a high energy discharge (Arcing). In period 2 showed the fault has moved DT zone where the engineer must pay more attention because the fault is at high energy zone which has a transition of two different type of thermal and electrical fault.

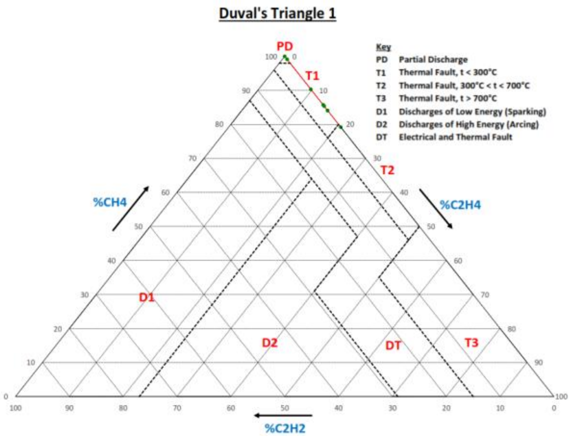
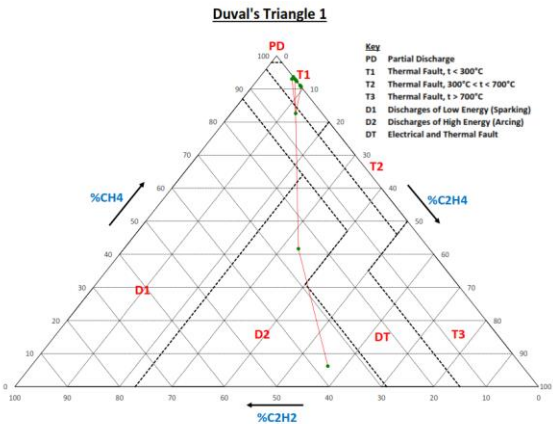
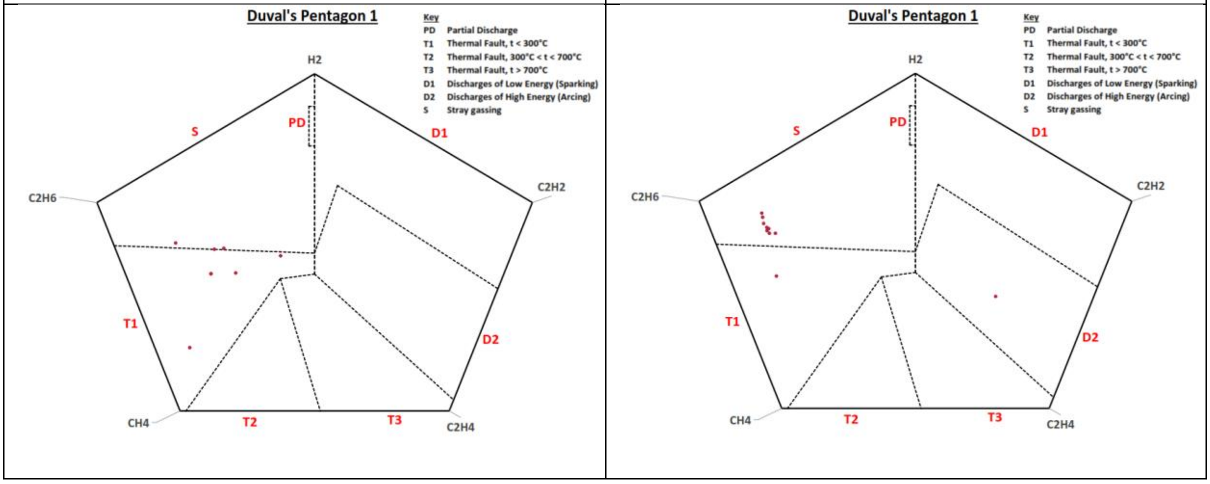
Period 1	Period 2
	

Figure 4-39: Case Study D - Duval's Triangle 1 – Period 1 and 2

4.4.5 Case Study D - Duval's Pentagon 1 Method

The Duval's Pentagon method (Figure 4-40) method started to diagnose this fault at PD zone to T1 region which is a low thermal fault level with the fault escalating discharge and to high energy discharge T2 fault region.



Period 1

Period 2

Figure 4-40: Case Study D - Duval's Pentagon 1 diagnostic results

4.4.6 Case Study D - LEDT and R-Value Trend

The LEDT will be presented for two periods, before and after it was taken out of service in March 2010.

The LEDT for period 1 in Figure 4-41 indicated that the transformer had a defect from commissioning due to the initial samples being in the abnormal D2 region confirming discharges. It must be pointed out that although the combustible gas trend did not indicate any concerns the LEDT was able to pick up discharges. The fault then progressed to the T2 region indicating a sustained thermal fault.

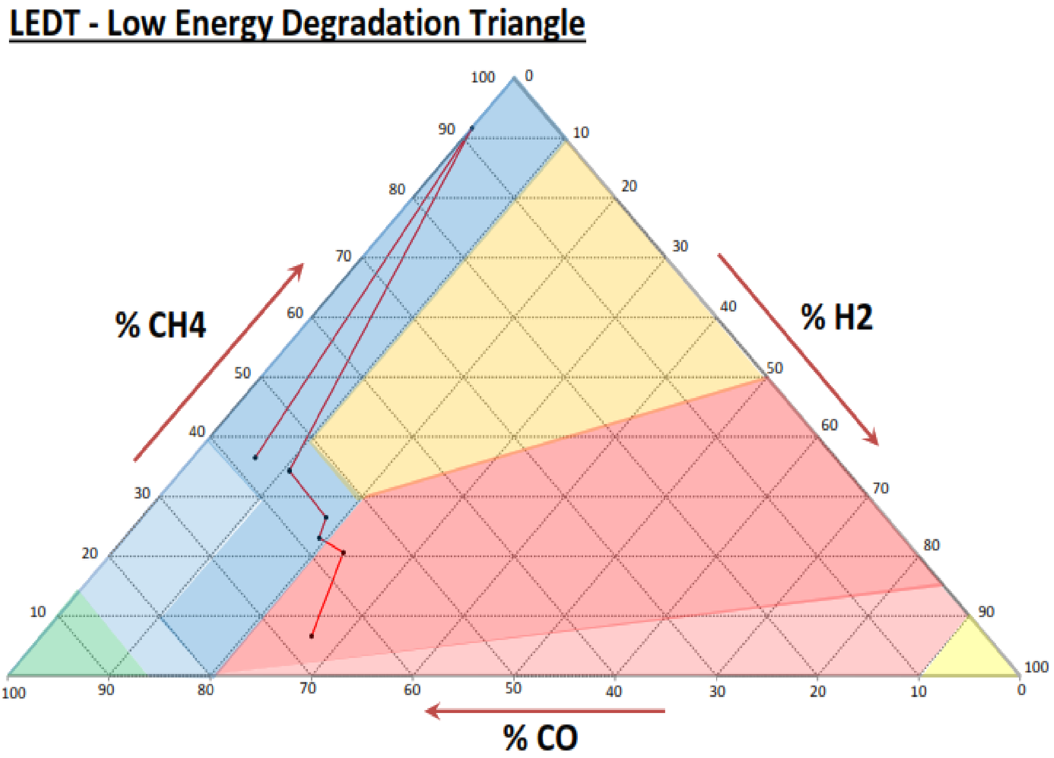


Figure 4-41: Case Study D - LEDT – Period 1

The R-Value (Figure 4-42) complimented the LEDT diagnostic results shown above and indicated that the defect was present.

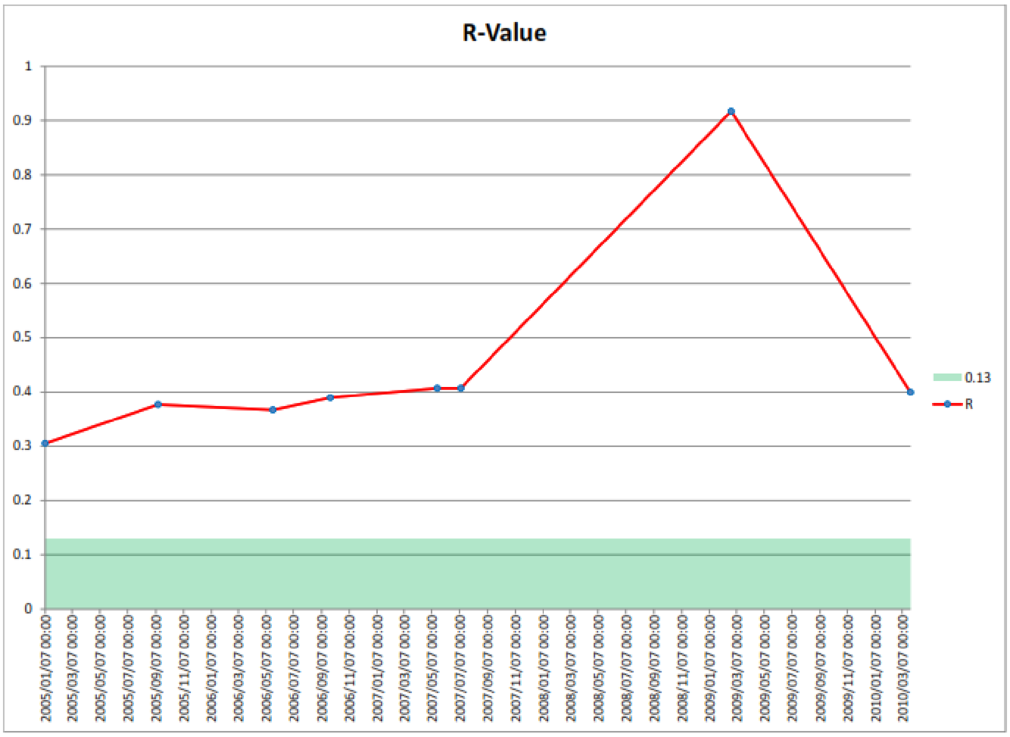


Figure 4-42: Case Study D - R-Value – Period 1

In Period 2 as displayed in Figure 4-43, when the transformer was returned to service it started in the green region and then with the steady increase of methane, ethane, and carbon monoxide the trend started to move back up into the T2 region still indicating the presence of a thermal fault.

No further interventions were done, and the transformer failed in October 2017.

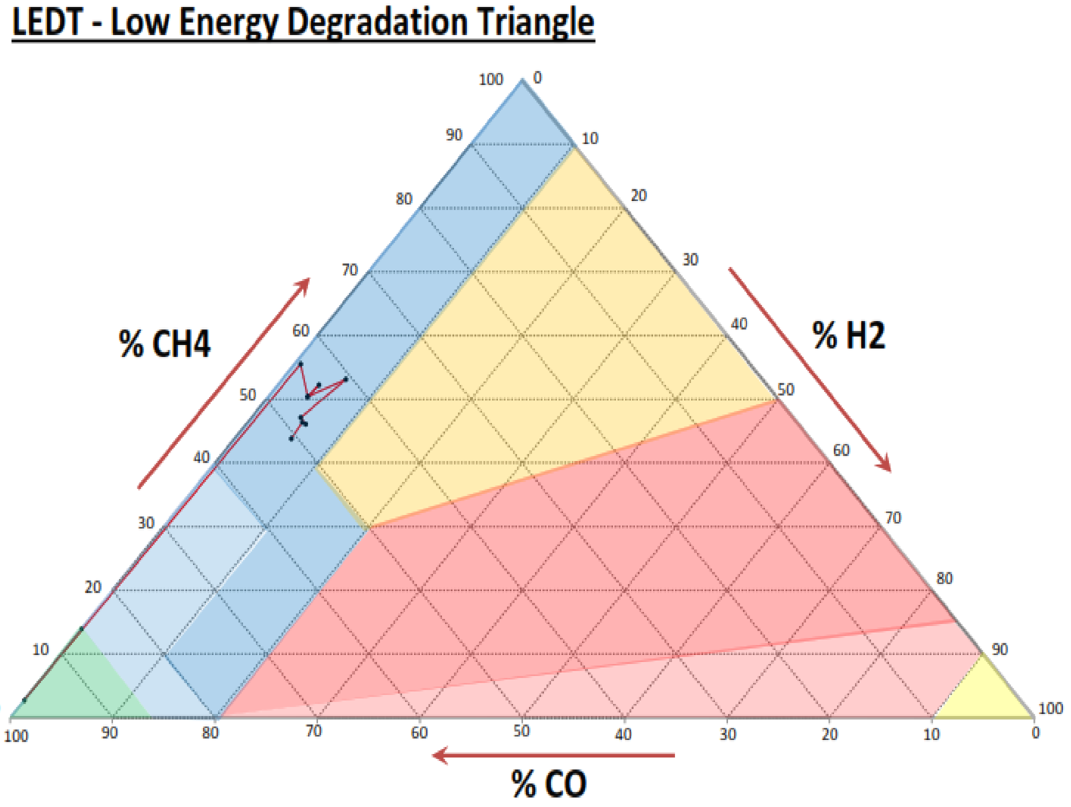


Figure 4-43: Case Study D - LEDT - Period 2

The R-value trend in Figure 4-44 confirms the movement form the normal region back into the abnormal fault region.

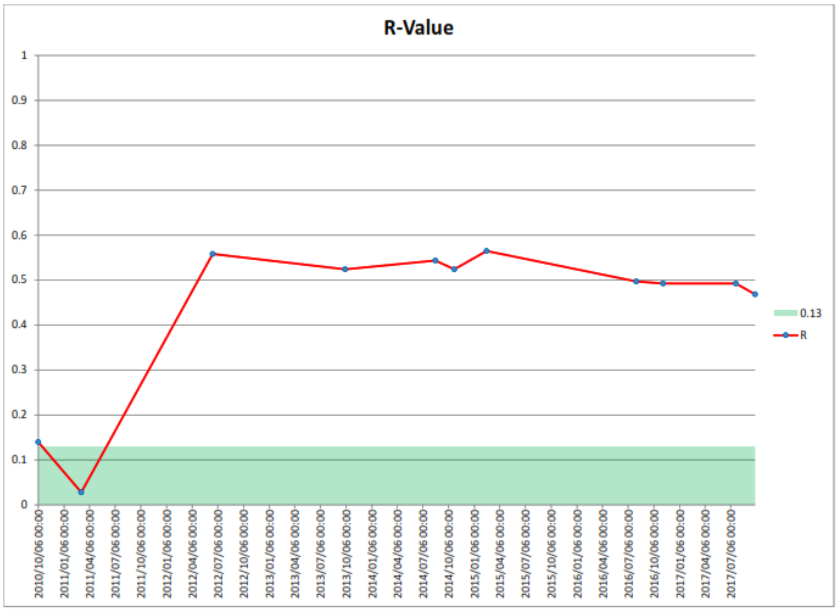


Figure 4-44: Case Study D - R-Value - Period 2

4.4.7 Case Study D - Extension of MEDT

The MEDT for period 1 (Figure 4-45) was also consistent in identify an initial fault with some progression. With movement along the ethane axis, it is indicative of a medium energy fault as the ethylene levels were constant. The R-value trend also provides a visual trend of the fault progression over time.

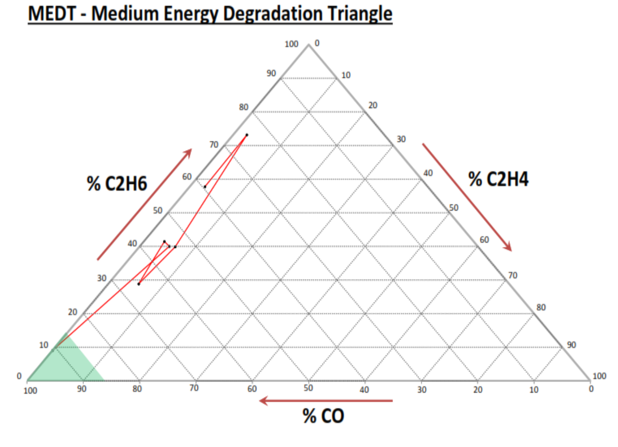
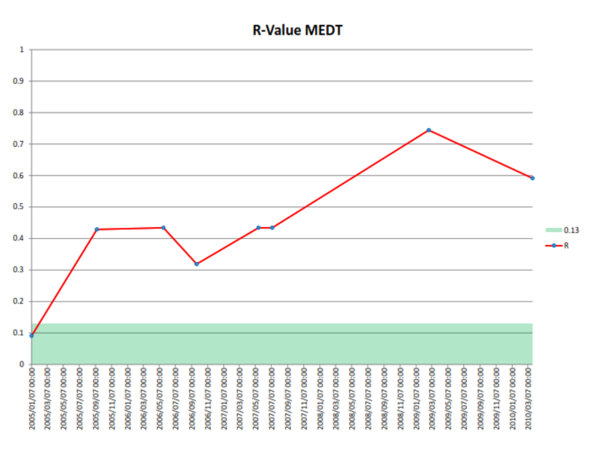
MEDT: Period 1	R-Value
	

Figure 4-45: MEDT and R-Value - Period 1

In period 2 the MEDT and related R-value trend (Figure 4-46), once again supports the diagnosis of the presence of a medium energy fault.

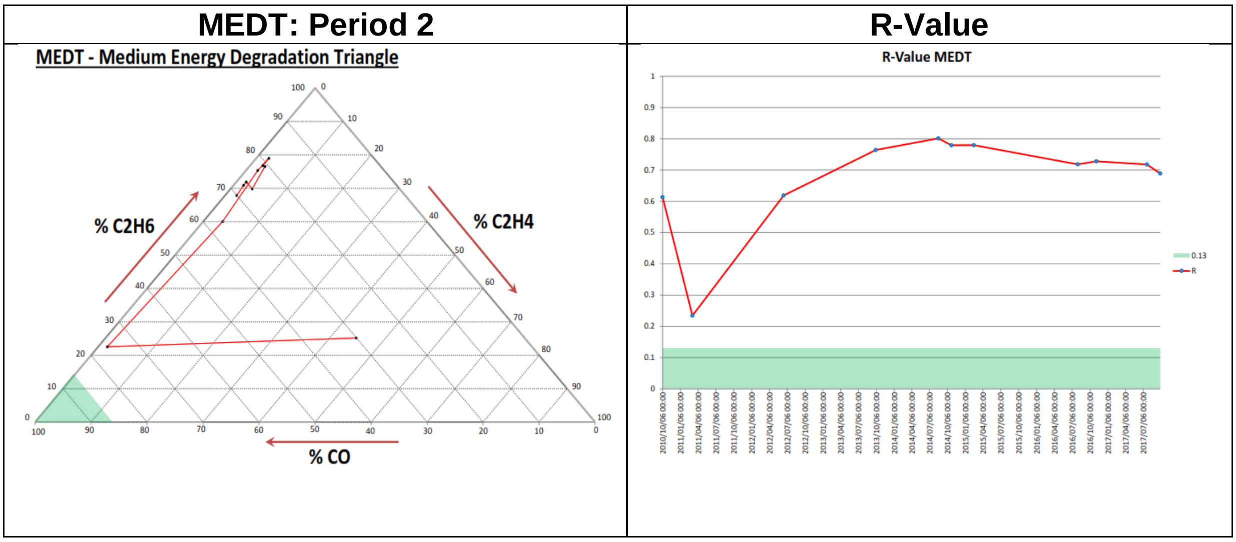


Figure 4-46: MEDT and R-Value - Period 2

4.4.8 Case Study D: Evaluation

The internal investigation was undertaken at the distribution substation identified a damaged disc winding on the white phase HV winding as picture in Figure 4-47. Furthermore, the copper of the winding had corrosive sulphur discolouration. When the transformer electrical was tested on-site, DC winding test results failed.

Both Duval's Triangle 1 and LEDT Method shows two T2 results medium thermal fault and high energy discharge D2 result zone. Whereas Duval's Pentagon 1 shows normal state result escalated to medium thermal fault T2 zone.

Figure 4-47: Faulted HV Winding

In this case study, the Roger's and Doernenburg ratios do not offer a consistent interpretation of the degradation or its trend. The Duval's Triangle 1 and pentagon indicate a trend in the type of damage occurring, but there is no indication of time. The LEDT and MEDT (each with R) indicate time-trends of different types of degradation, which can give an early indication of a problem and aid inspection. Duval's Pentagon 1, LEDT Method 1 and Duval's Triangle 1 all showed that they complementary each other with their diagnose results and all started at PD zone and end at high energy discharge zone.

The root cause of transformer failure was electrical fault caused by intern-turn of windings.

4.5 Case Study E: 765KV: 145MVAR, YOM: 2000

4.5.1 Background and Root Cause Analysis

This shunt reactor was manufactured in 2000 and commissioned the same year at a transmission substation on the South Grid. All reactors in the transmission network were operated at full load.

The first commissioning oil samples were taken in June 2000 and the oil results indicated unexpected escalation of methane (CH_4), ethane (C_2H_6) and carbon monoxide (CO) until 2007 when the shunt reactor was de-energized from the network for electrical test and visual inspection. The reactor was put back on load in 2008 and the same fault gases escalated again. In January 2018, the shunt reactor was de-energised again from the network for internal inspection to be carried out and this was where the oil was processed. When the shunt reactor was returned to service in July 2018 the carbon monoxide started showing escalation and other combustible gases were stable.

Therefore, the shunt reactor is in service and continued with stabilising the network at transmission lines.

4.5.2 Case Study E - Combustible Gas Trend

Figure 4-48 provides a combustible gas trend of the dissolved gas results over the period. Ethane, methane and carbon monoxide has been fluctuating over the whole period, Hydrogen, ethylene and acetylene have been consistently low.

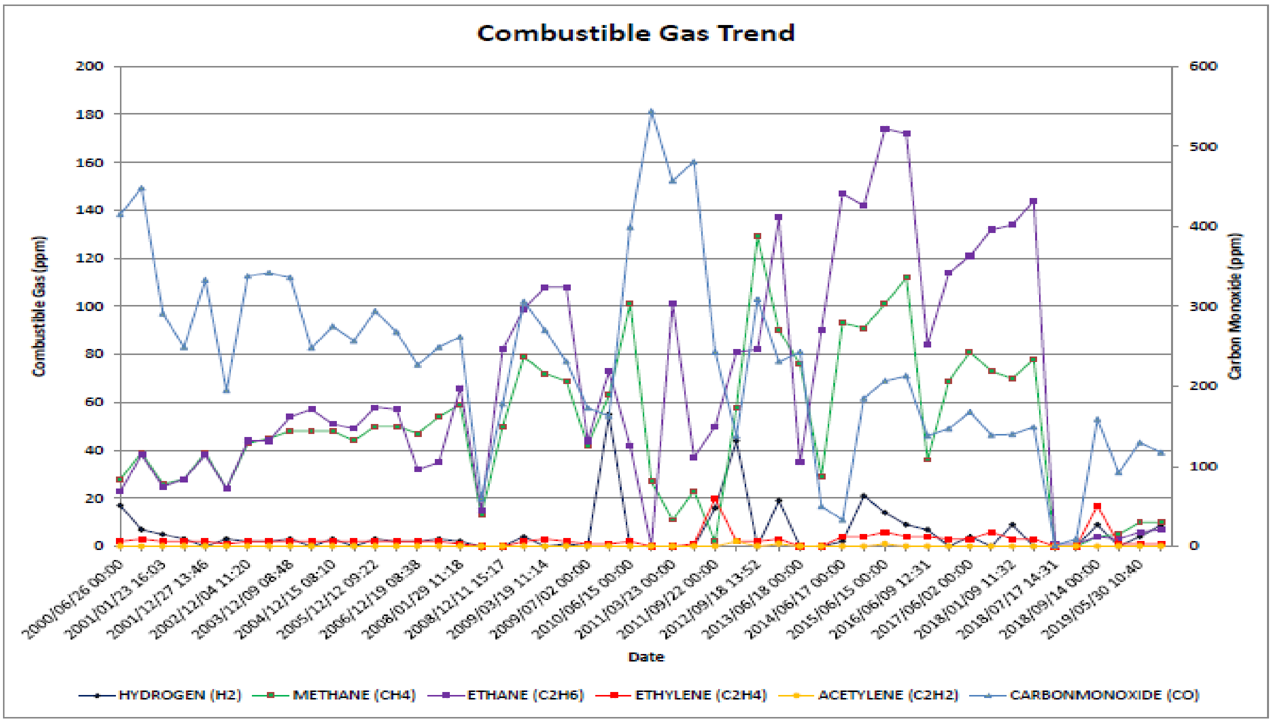
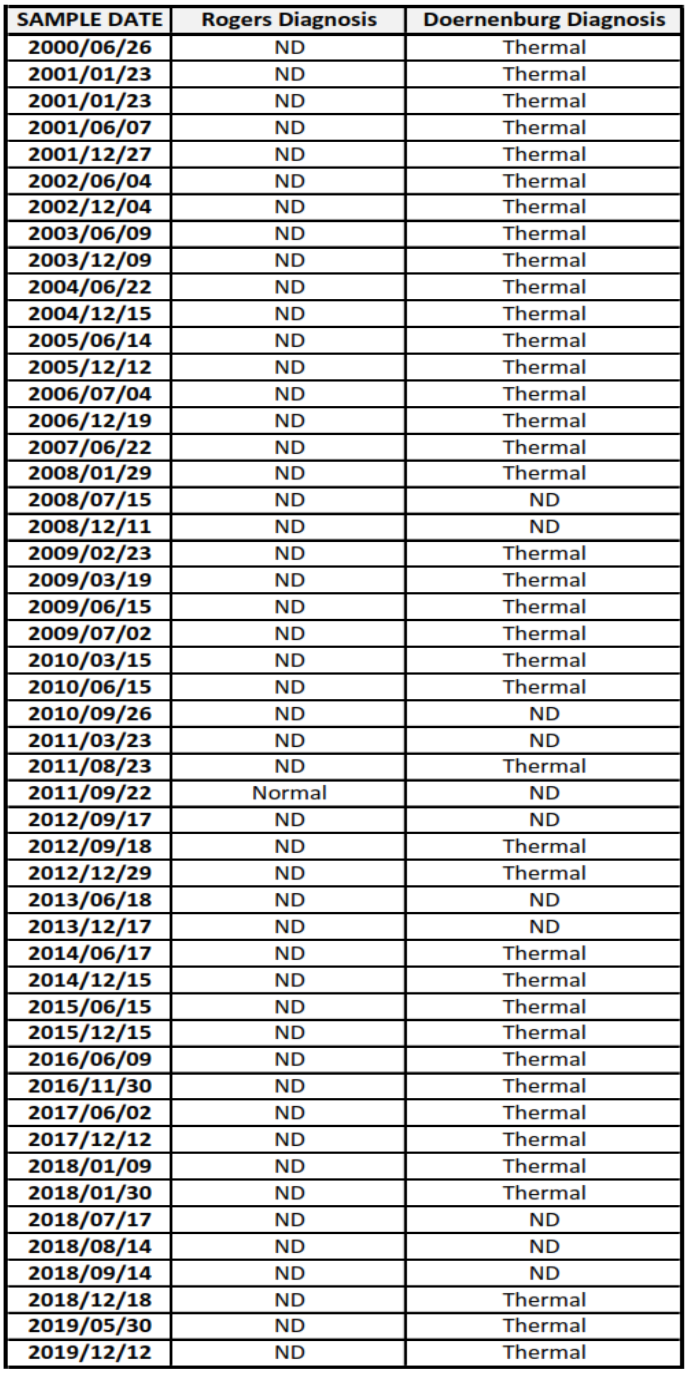


Figure 4-48: Case Study E - Combustible Gas Trend

4.5.3 Case Study E - Rogers and Doernenburg Ratio Methods

Roger’s and Doernenburg ratios were taken for the full sample range as indicated in Table 4-5. ND represents no diagnosis where Roger’s ratio method had 98% and Doernenburg method had 22% ND diagnosis. It is observed that Roger’s ratio had only one diagnosis of “thermal > 700°C”. Doernenburg ratio had a diagnosis of “PD” and “Thermal”.

Table 4-5: Case Study E - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
2000/06/26	ND	Thermal
2001/01/23	ND	Thermal
2001/01/23	ND	Thermal
2001/06/07	ND	Thermal
2001/12/27	ND	Thermal
2002/06/04	ND	Thermal
2002/12/04	ND	Thermal
2003/06/09	ND	Thermal
2003/12/09	ND	Thermal
2004/06/22	ND	Thermal
2004/12/15	ND	Thermal
2005/06/14	ND	Thermal
2005/12/12	ND	Thermal
2006/07/04	ND	Thermal
2006/12/19	ND	Thermal
2007/06/22	ND	Thermal
2008/01/29	ND	Thermal
2008/07/15	ND	ND
2008/12/11	ND	ND
2009/02/23	ND	Thermal
2009/03/19	ND	Thermal
2009/06/15	ND	Thermal
2009/07/02	ND	Thermal
2010/03/15	ND	Thermal
2010/06/15	ND	Thermal
2010/09/26	ND	ND
2011/03/23	ND	ND
2011/08/23	ND	Thermal
2011/09/22	Normal	ND
2012/09/17	ND	ND
2012/09/18	ND	Thermal
2012/12/29	ND	Thermal
2013/06/18	ND	ND
2013/12/17	ND	ND
2014/06/17	ND	Thermal
2014/12/15	ND	Thermal
2015/06/15	ND	Thermal
2015/12/15	ND	Thermal
2016/06/09	ND	Thermal
2016/11/30	ND	Thermal
2017/06/02	ND	Thermal
2017/12/12	ND	Thermal
2018/01/09	ND	Thermal
2018/01/30	ND	Thermal
2018/07/17	ND	ND
2018/08/14	ND	ND
2018/09/14	ND	ND
2018/12/18	ND	Thermal
2019/05/30	ND	Thermal
2019/12/12	ND	Thermal

4.5.4 Case Study E - Duval’s Triangle 1 Method

Duval’s Triangle 1 measurement results confirmed that the transformer was overheating during the operation. This method started measurement the incipient fault at PD moved to T1 and this fault escalated to thermal fault T3 which was greater than 700˚C.

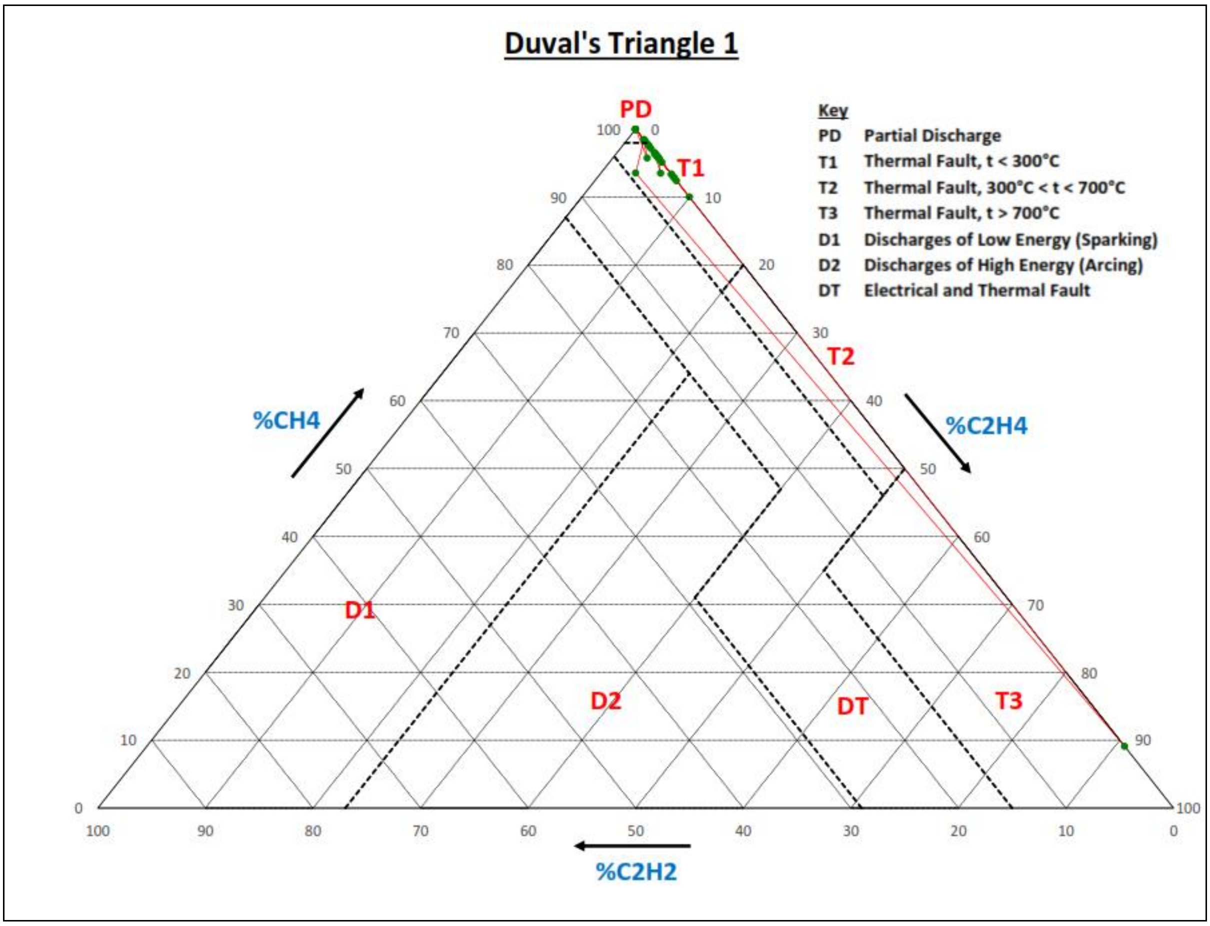


Figure 4-49: Case Study E - Duval’s Triangle 1

4.5.5 Case Study E - Duval’s Pentagons 1 Method

The Duval’s Pentagon method in Figure 4-50 indicated the gas trend that started measurement at low temperature stage and escalate till the mixture of electrical and thermal fault started at T3 and D2, where fault energy is greater than 700°C.

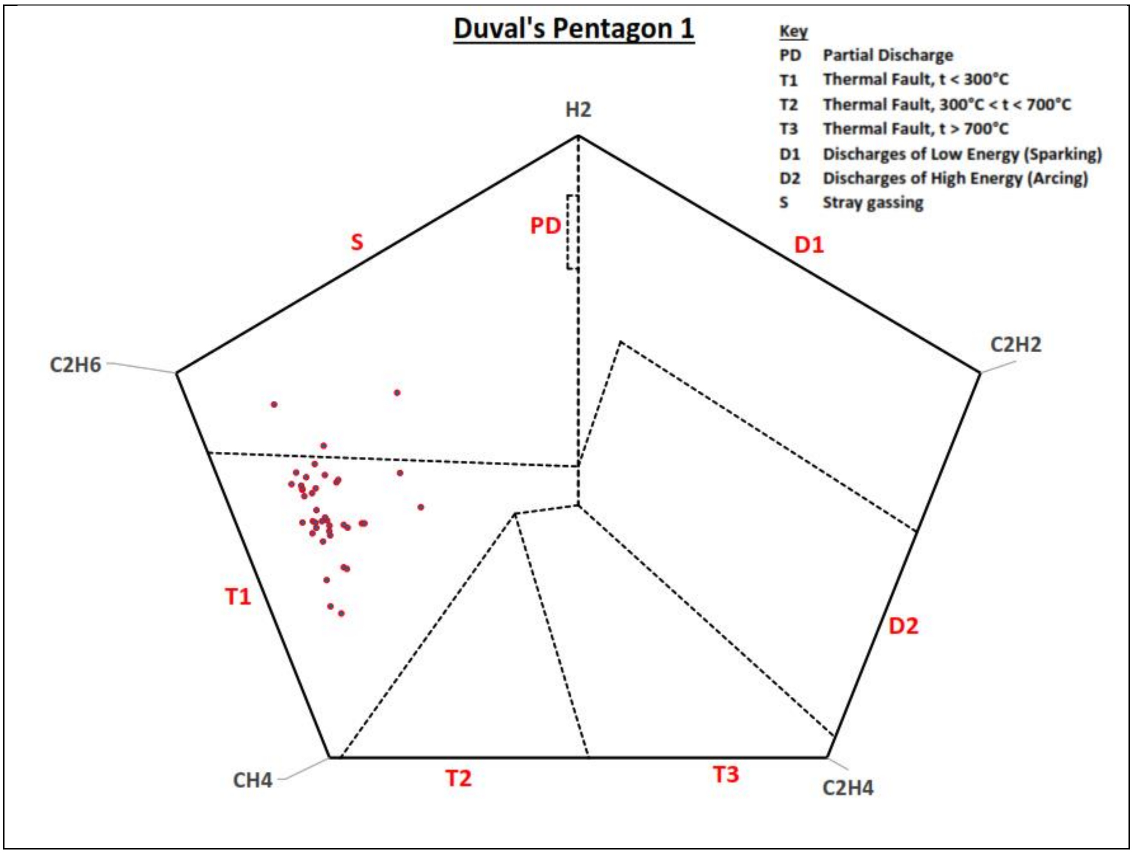


Figure 4-50: Case Study E - Duval's Pentagon 1 diagnosis

4.5.6 Case Study E - LEDT and R-Value Trend

From Figure 4-51, the LEDT starts off from 2002-3 in the green region and the slowly progresses into the T1 region from 2004 onwards to 2010. In 2011 the reactor is taken out and reinstalled where the samples now are in the green region but then quickly moves to a T2 fault region in 2012 where it settles down in the T1 region again from 2012 until 2018.

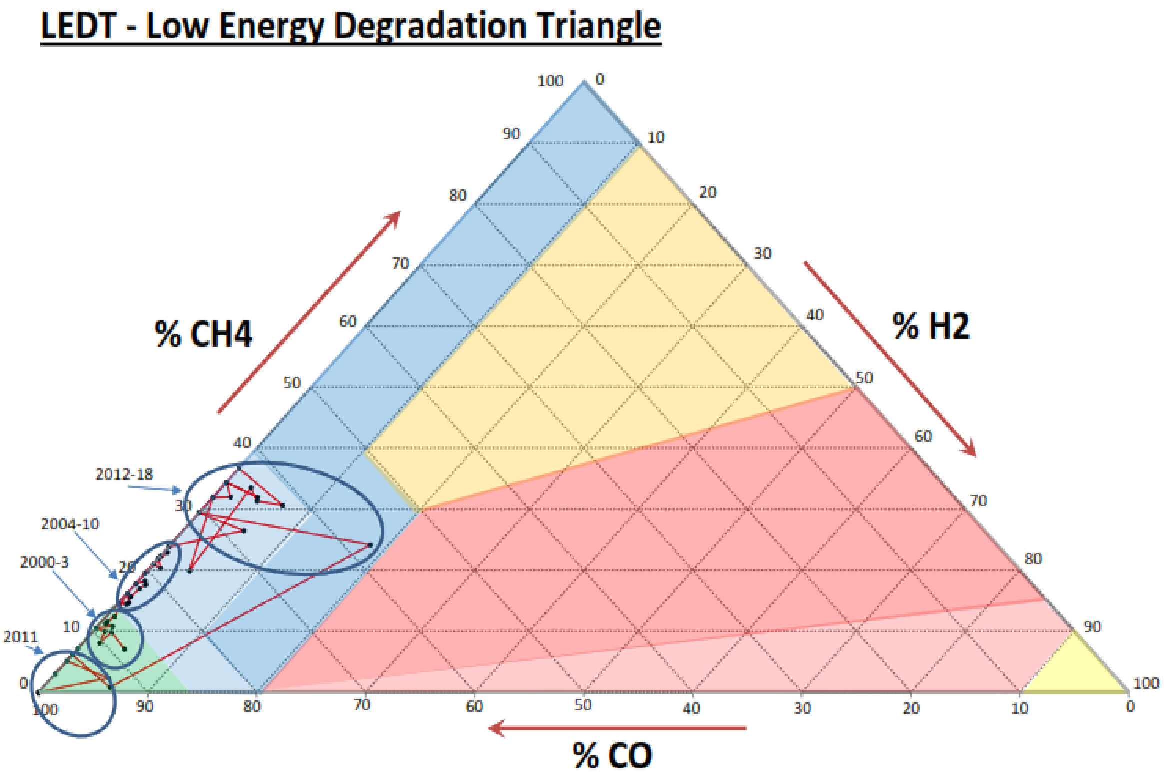


Figure 4-51: Case Study E - LEDT

From the R-value trend in Figure 4-52 it can be seen how the transformer progressed into the T1 region and the results were consistent with the transformer coming out of service both time but indicating that there was still elevation of combustible gases and the problem still being evident.

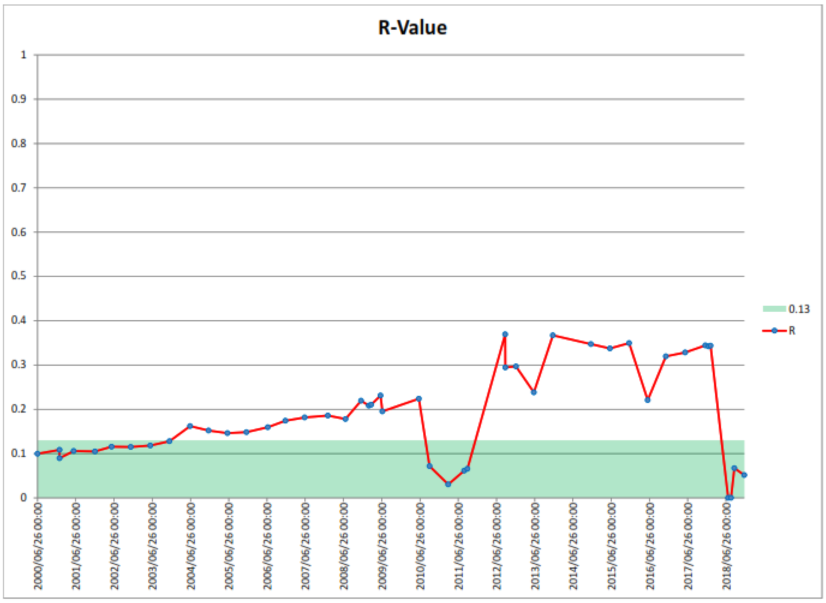


Figure 4-52: Case Study E - R-Value

4.5.7 Case Study E - Extension of MEDT

The MEDT was also consistent in indicating the progression of the fault from the green region to the abnormal condition along the ethane axis. It is also clear that the level of ethylene is also constant with no significant increases.

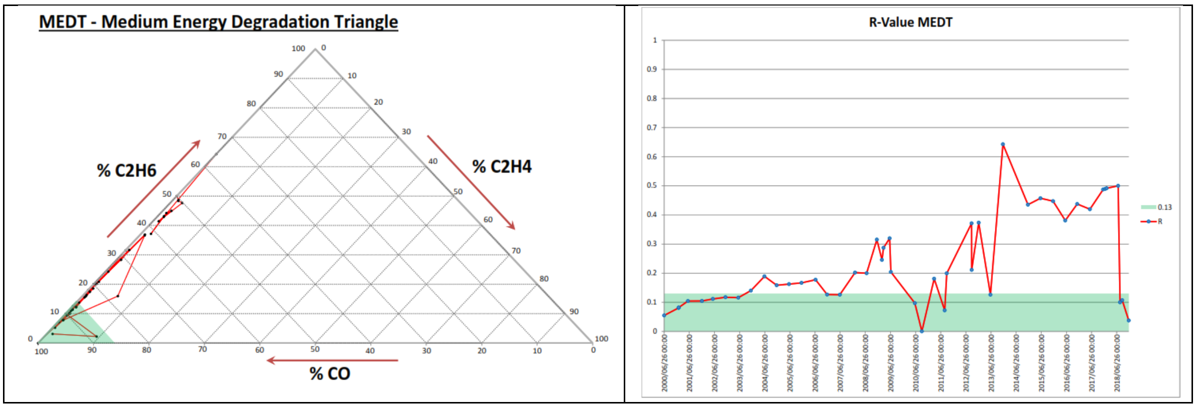


Figure 4-53: MEDT and R-Value

4.5.8 Case Study E: Evaluation

A visual inspection was undertaken at the transmission substation before an internal inspection was carried out. Externally, closed cooler banks were observed and internally damage components were also observed. See Figure 4-54 and Figure 4-55 respectively. The defects observed were in line with the gas pattern that was elevated in the shunt reactor from first commissioned. LEDT Method1 complementary the diagnose results from Duval's Pentagon 1. Their fault gas started from normal zone to low temperature rate. However, Duval's Triangle 1 and Roger's Ratio does not detect the fault at low temperature as mentioned at IEEE C57.104-2008 guidelines and they started at PD discharge zone.

The root cause was loose nuts from the shunt and the thermal fault started led the elevation of the fault to partial discharge.

Figure 4-54: Short lamination on return limb

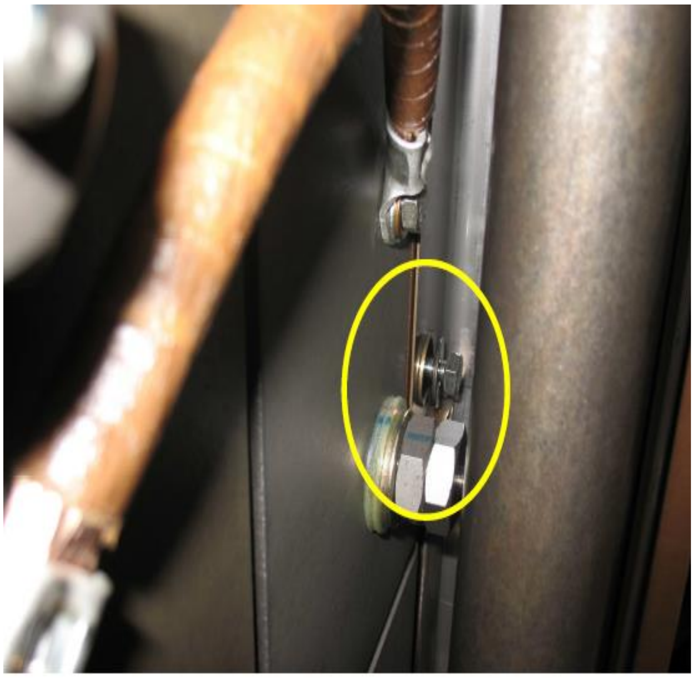


Figure 4-55: Loose nuts on shunts

4.6 Case Study F: 275/132/22KV: 250MVA, YOM: 1977

4.6.1 Background and Root Cause Analysis

This transformer was manufactured in 1977 and 1991 was shipped from strategic spares storage to the transmission substation for installation of the central Grid. The transformer was sharing the load with the sister unit to comply with the transmission strategy of N-1 capacity.

In September 1991, the installation of this transformer was carried out with the first oil samples taken indicating normal status except for carbon monoxide that was constantly increasing. The combustible gas trend kept on stable till the transformer tripped on the 12th of February of 2018 and where the internal inspection was conducted.

When the transformer was taken back to service on the 26th of April 2018, the combustible gases suddenly escalated. The transformer was taken out from service again and moved to the workshop for further investigation.

During this period, the transformer was running without outage from the network. The transformer has an oil type online tap changer where the selector switch shares oil with main tank oil.

4.6.2 Case Study F - Combustible gas trend

Figure 4-57 provides a combustible gas trend of the dissolved gas results over the period. Since this transformer was first installed in 1991, the combustible gases were normal, but the carbon monoxide levels were erratic until the 12th of February 2018 when the transformer was on outage. The transformer came back to service on the 18th 0f Apr 2018, and all combustible gases were increasing. On the 27th of April 2018, the transformer was taken out of service for further investigation.

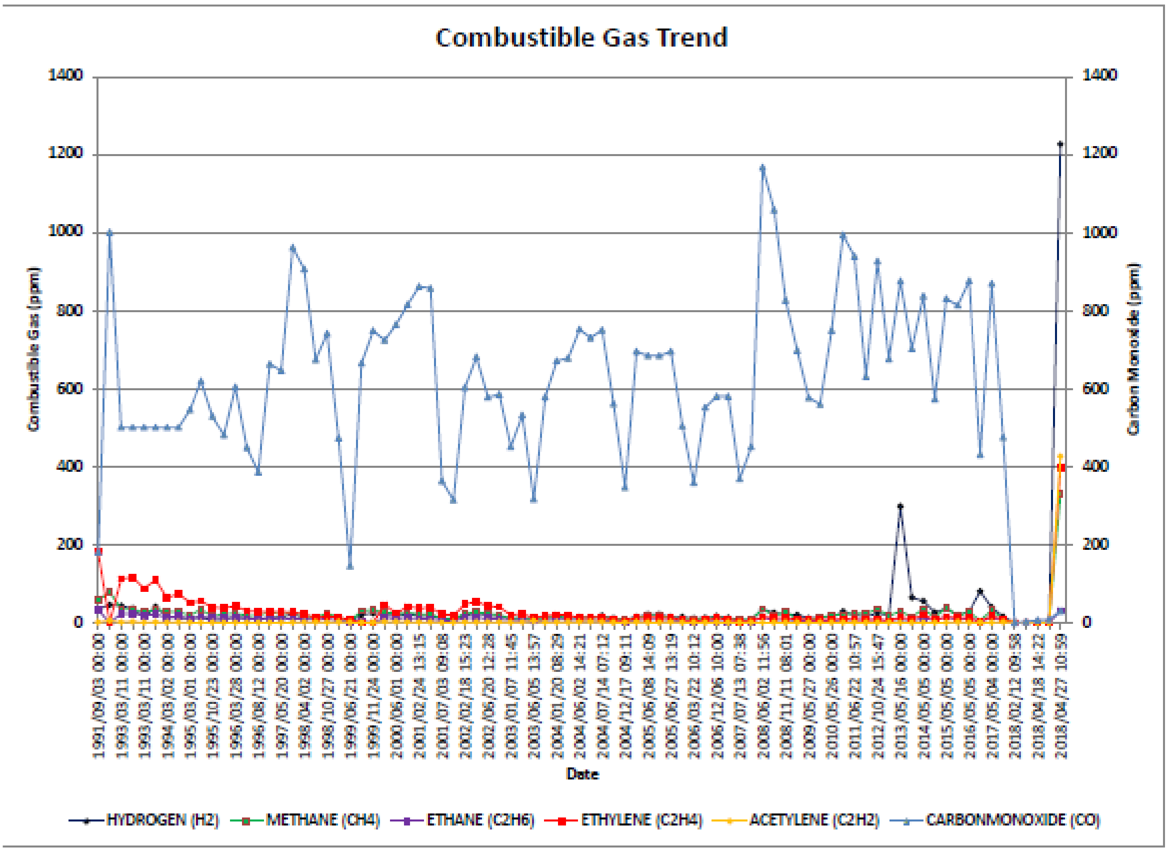
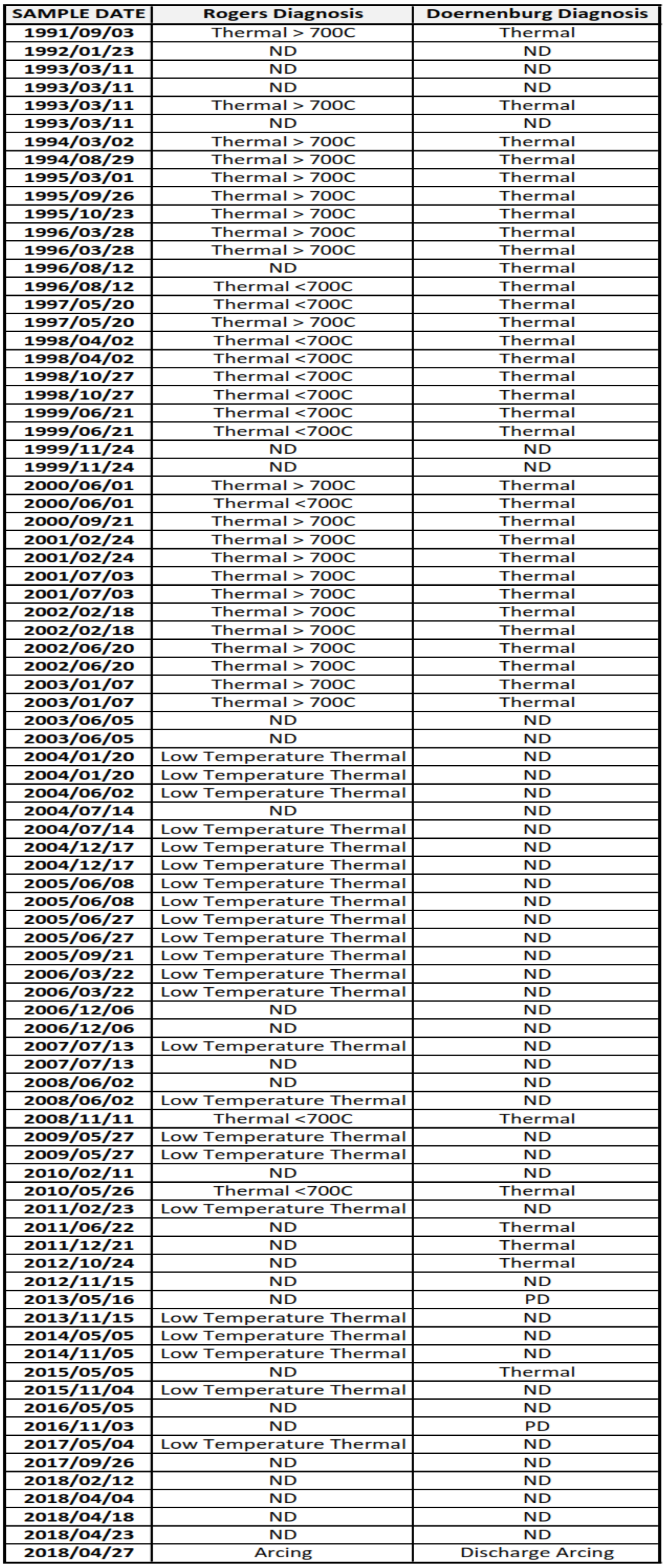


Figure 4-56: Case Study F - Combustible Gas Trend

4.6.3 Case Study F - Rogers and Doernenburg Ratio Methods

Roger’s and Doernenburg ratios were taken for the full sample range as indicated in Table 4-6. ND represents no diagnosis where Roger’s ratio method had 33% and Doernenburg method had 52% ND diagnosis. It is observed that both Rogers and Doernenburg method did have a significant diagnosis the thermal faults.

Table 4-6: Case Study F - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
1991/09/03	Thermal > 700C	Thermal
1992/01/23	ND	ND
1993/03/11	ND	ND
1993/03/11	ND	ND
1993/03/11	Thermal > 700C	Thermal
1993/03/11	ND	ND
1994/03/02	Thermal > 700C	Thermal
1994/08/29	Thermal > 700C	Thermal
1995/03/01	Thermal > 700C	Thermal
1995/09/26	Thermal > 700C	Thermal
1995/10/23	Thermal > 700C	Thermal
1996/03/28	Thermal > 700C	Thermal
1996/03/28	Thermal > 700C	Thermal
1996/08/12	ND	Thermal
1996/08/12	Thermal <700C	Thermal
1997/05/20	Thermal <700C	Thermal
1997/05/20	Thermal > 700C	Thermal
1998/04/02	Thermal <700C	Thermal
1998/04/02	Thermal <700C	Thermal
1998/10/27	Thermal <700C	Thermal
1998/10/27	Thermal <700C	Thermal
1999/06/21	Thermal <700C	Thermal
1999/06/21	Thermal <700C	Thermal
1999/11/24	ND	ND
1999/11/24	ND	ND
2000/06/01	Thermal > 700C	Thermal
2000/06/01	Thermal <700C	Thermal
2000/09/21	Thermal > 700C	Thermal
2001/02/24	Thermal > 700C	Thermal
2001/02/24	Thermal > 700C	Thermal
2001/07/03	Thermal > 700C	Thermal
2001/07/03	Thermal > 700C	Thermal
2002/02/18	Thermal > 700C	Thermal
2002/02/18	Thermal > 700C	Thermal
2002/06/20	Thermal > 700C	Thermal
2002/06/20	Thermal > 700C	Thermal
2003/01/07	Thermal > 700C	Thermal
2003/01/07	Thermal > 700C	Thermal
2003/06/05	ND	ND
2003/06/05	ND	ND
2004/01/20	Low Temperature Thermal	ND
2004/01/20	Low Temperature Thermal	ND
2004/06/02	Low Temperature Thermal	ND
2004/07/14	ND	ND
2004/07/14	Low Temperature Thermal	ND
2004/12/17	Low Temperature Thermal	ND
2004/12/17	Low Temperature Thermal	ND
2005/06/08	Low Temperature Thermal	ND
2005/06/08	Low Temperature Thermal	ND
2005/06/27	Low Temperature Thermal	ND
2005/06/27	Low Temperature Thermal	ND
2005/09/21	Low Temperature Thermal	ND
2006/03/22	Low Temperature Thermal	ND
2006/03/22	Low Temperature Thermal	ND
2006/12/06	ND	ND
2006/12/06	ND	ND
2007/07/13	Low Temperature Thermal	ND
2007/07/13	ND	ND
2008/06/02	ND	ND
2008/06/02	Low Temperature Thermal	ND
2008/11/11	Thermal <700C	Thermal
2009/05/27	Low Temperature Thermal	ND
2009/05/27	Low Temperature Thermal	ND
2010/02/11	ND	ND
2010/05/26	Thermal <700C	Thermal
2011/02/23	Low Temperature Thermal	ND
2011/06/22	ND	Thermal
2011/12/21	ND	Thermal
2012/10/24	ND	Thermal
2012/11/15	ND	ND
2013/05/16	ND	PD
2013/11/15	Low Temperature Thermal	ND
2014/05/05	Low Temperature Thermal	ND
2014/11/05	Low Temperature Thermal	ND
2015/05/05	ND	Thermal
2015/11/04	Low Temperature Thermal	ND
2016/05/05	ND	ND
2016/11/03	ND	PD
2017/05/04	Low Temperature Thermal	ND
2017/09/26	ND	ND
2018/02/12	ND	ND
2018/04/04	ND	ND
2018/04/18	ND	ND
2018/04/23	ND	ND
2018/04/27	Arcing	Discharge Arcing

4.6.4 Case Study F - Duval's Triangle 1 Method

Duval's method started indicating the incipient fault as a partial discharge before progressing and into the T2 and T3 regions. Thermal fault escalated to DT fault zone where the mixture of two different type of thermal/electrical fault occurred the transition from thermal to electrical fault.

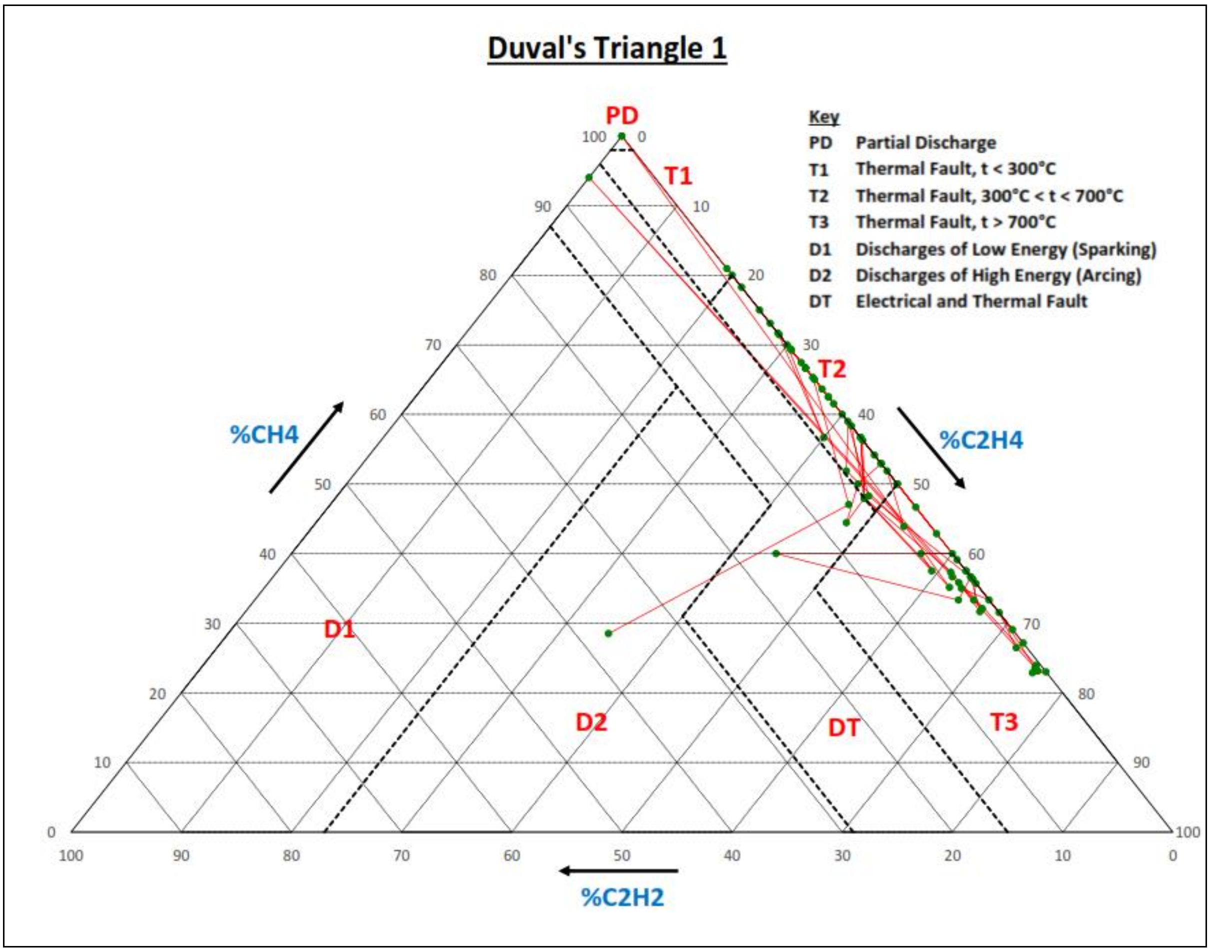


Figure 4-57: Duval's Triangle 1 Method

4.6.5 Case Study F - Duval's Pentagons Method

Duval's Pentagons method in Figure 4-58 provides information of the initial low partial discharge charges which then progress to D2 discharges of high energy.

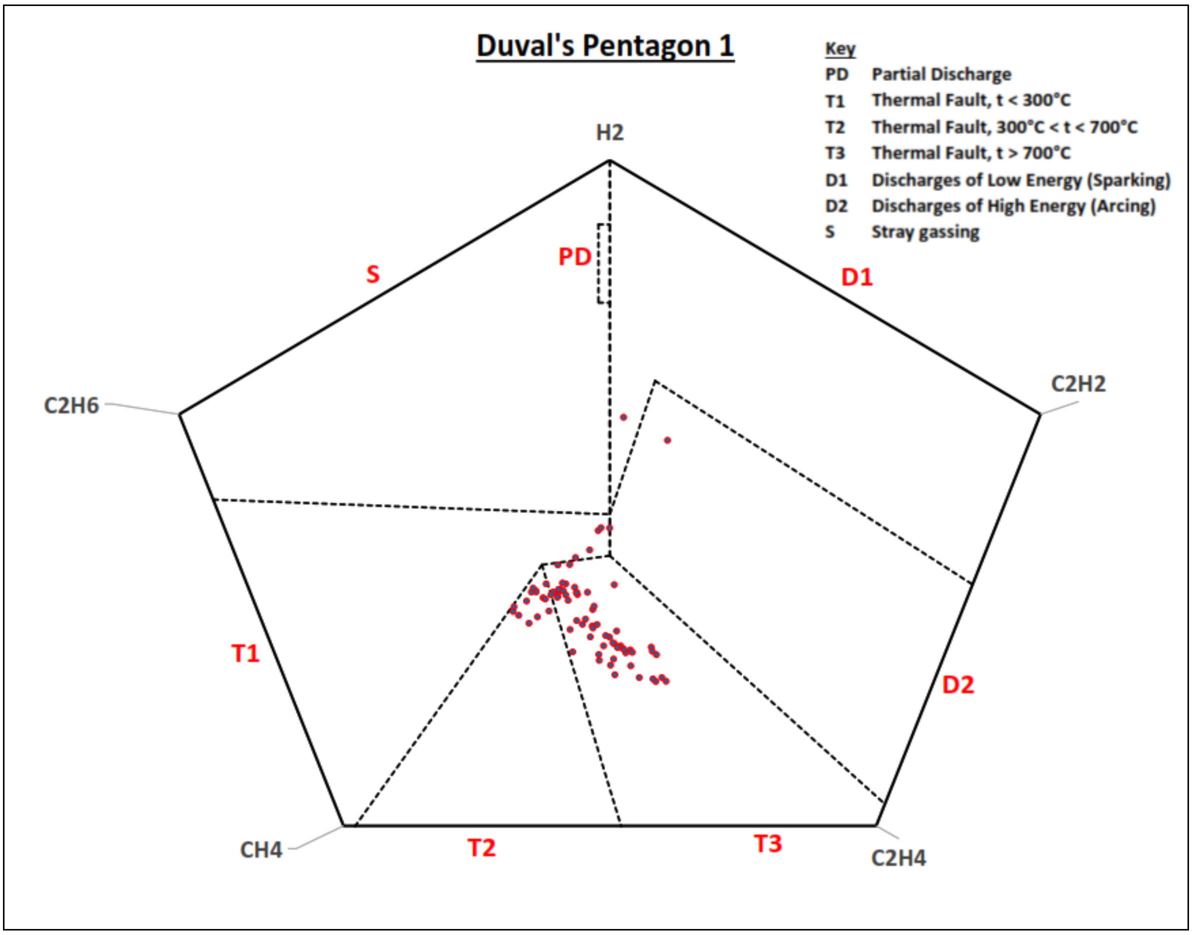


Figure 4-58: Case Study F - Duval's Pentagons 1 Method

4.6.6 Case Study F - Low Energy Degradation Triangle

From the LEDT as presented in Figure 4-59 it is found with the initial commissioning in 1991 the transformer was in the T2 fault region after which it the moved slowly to the T1 in 1992 and the normal region in 1993. It remained in this area and had one incident in 2013 where it moves to the D1 region and eventually failed in 2018.

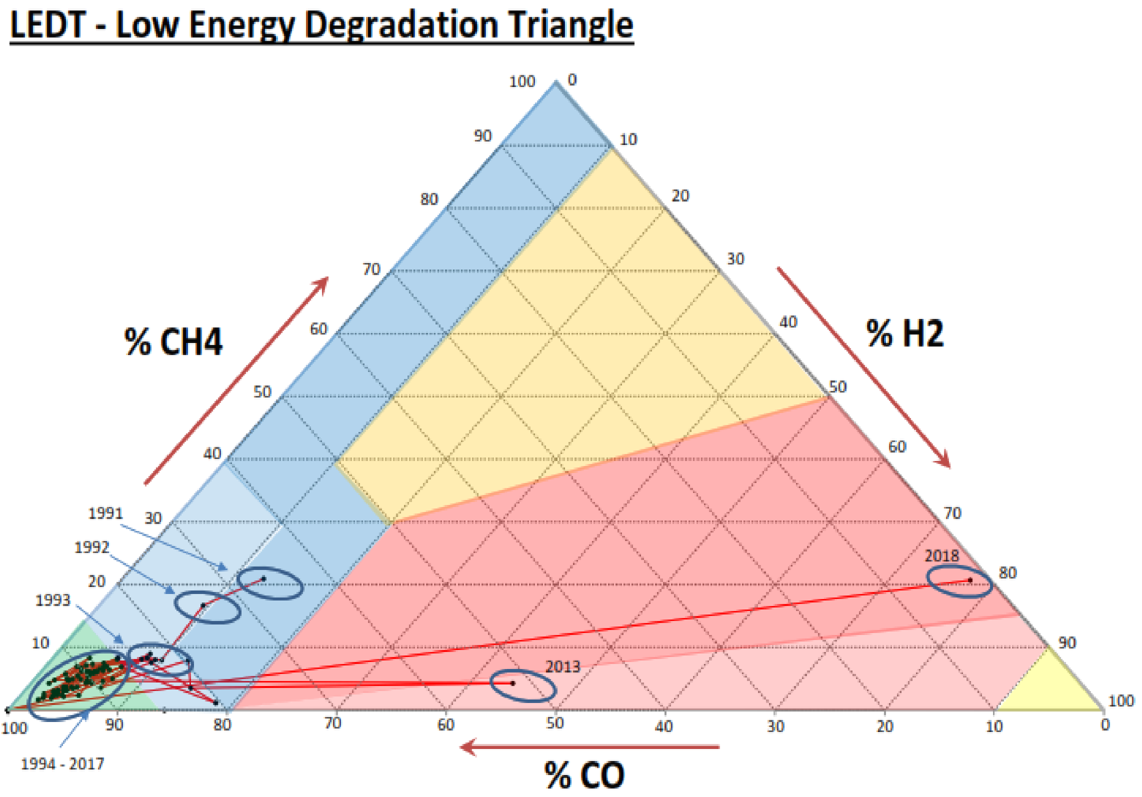


Figure 4-59: Case Study F - LEDT

This is also evident from the R-Value trend in Figure 4-60. With the initial samples being outside the normal region and then fluctuating on the normal region until failure in 2018.

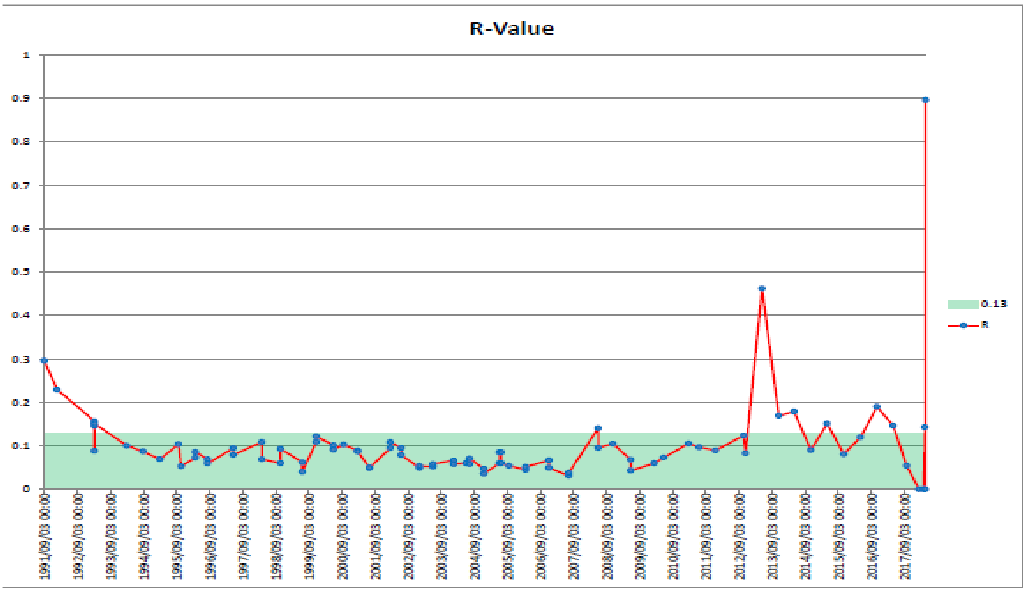


Figure 4-60: Case Study F - R-Value

4.6.7 Case Study F - Extension MEDT

The MEDT and related R-value trend in Figure 4-61 also portrays the same trend as the LEDT.

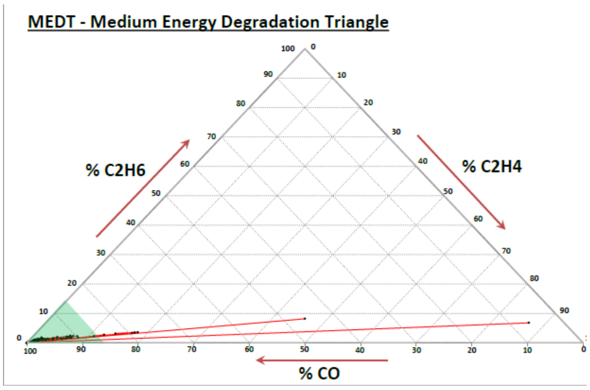
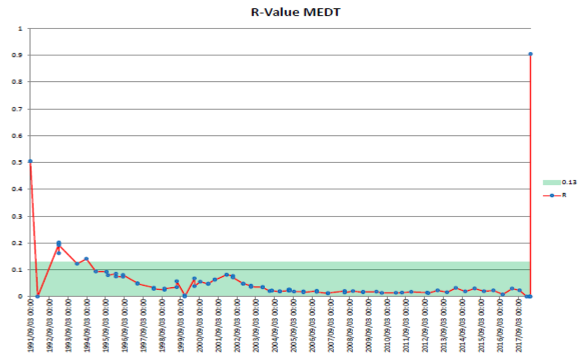
MEDT	R-Value
	

Figure 4-61: MEDT and R-Value

4.6.8 Case Study F: Evaluation

During an internal investigation, many active components were found damaged inside the transformer tank. Figure 4-62 indicated the severe arc mark on the base of the tap changer barrel. The failure of this transformer was unexpected. The root cause of failure for this transformer was given as the end of life, concluding that the failure was first mechanical, and clearance compromised and electrically arced to another potential different component.

Figure 4-62: Damaged tap changer barrel

This transformer did not show any sign of unhealthy before it failed, however, the DGA pattern was indicating the low energy thermal fault. It is, therefore, concluded that the failure of this transformer was sudden and unexpected.

LEDT Methos indicated the fault gas started from normal zone and moved to T1, T2 medium thermal fault. In 2013 the fault gas was at D1 and moved to high energy discharge D2 zone. The R-Value shows the status of the fault that is in the visible stage. MEDT complement the diagnose result by LEDT Method.

Duval’s Triangle 1 shows where the fault gas started from PD zone, spiked to high energy discharge in the D2 zone, developed into low thermal T1 and to high thermal fault T3 and DT zone which is the transition zone for thermal and electrical fault results. Duval’s Pentagon 1 shows high thermal fault T2, T3 and high energy discharge D2.

CO was previously considered to be a product of paper degradation [IEEE C57.104] but the threshold levels of concern are high. The high levels evident in this case masked the combustible gases.

4.7 Case Study G: 400/132/22KV: 250MVA, YOM: 1976

4.7.1 Background and Root Cause Analysis

This transformer was manufactured in 1976 and was commissioned at a transmission substation. There is currently no evidence of this transformer having been moved around or being at the workshop for repairs. The transformer was loaded according to the transmission strategy of N-1 capacity.

The commissioning oil sample was taken in August 1992 and oil results were clear except carbon monoxide was increasing with some hydrogen and methane. In 2011 there was a sudden generation of ethane, ethylene, and sporadic increases of acetylene. This remained stable until September 2018, where the Buchholz alarm was initiated. The transformer was then de-energised from the network to investigate, bleed and reset the Buchholz relay, and then returned into service, 5 hours later, another Buchholz alarm came up. The transformer was taken out from the network, where the electrical tests were conducted as part of the investigation and the test results showed no deviations in the electrical circuit of the transformer.

4.7.2 Case Study G - Combustible Gas Trend

Figure 4-63 provides a combustible gas trend of the dissolved gas results over the period. In 2007 the acetylene levels started to come up indicating that a possible fault was present. Between November 2011 and May 2012, the fault got into an advanced stage where all the gasses increased.

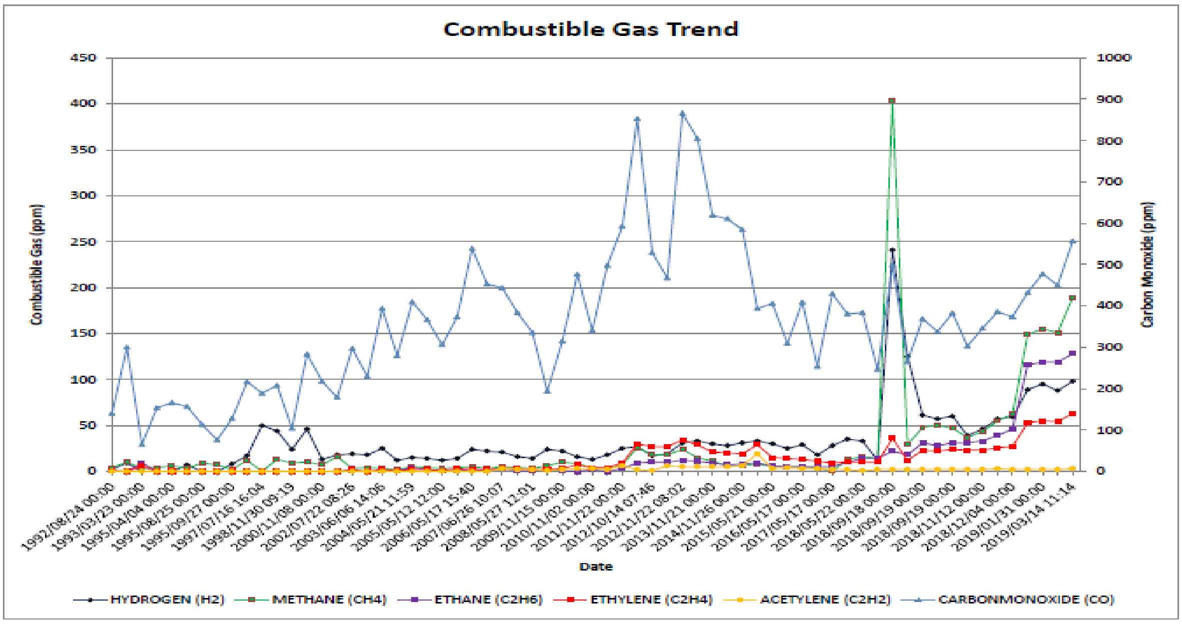
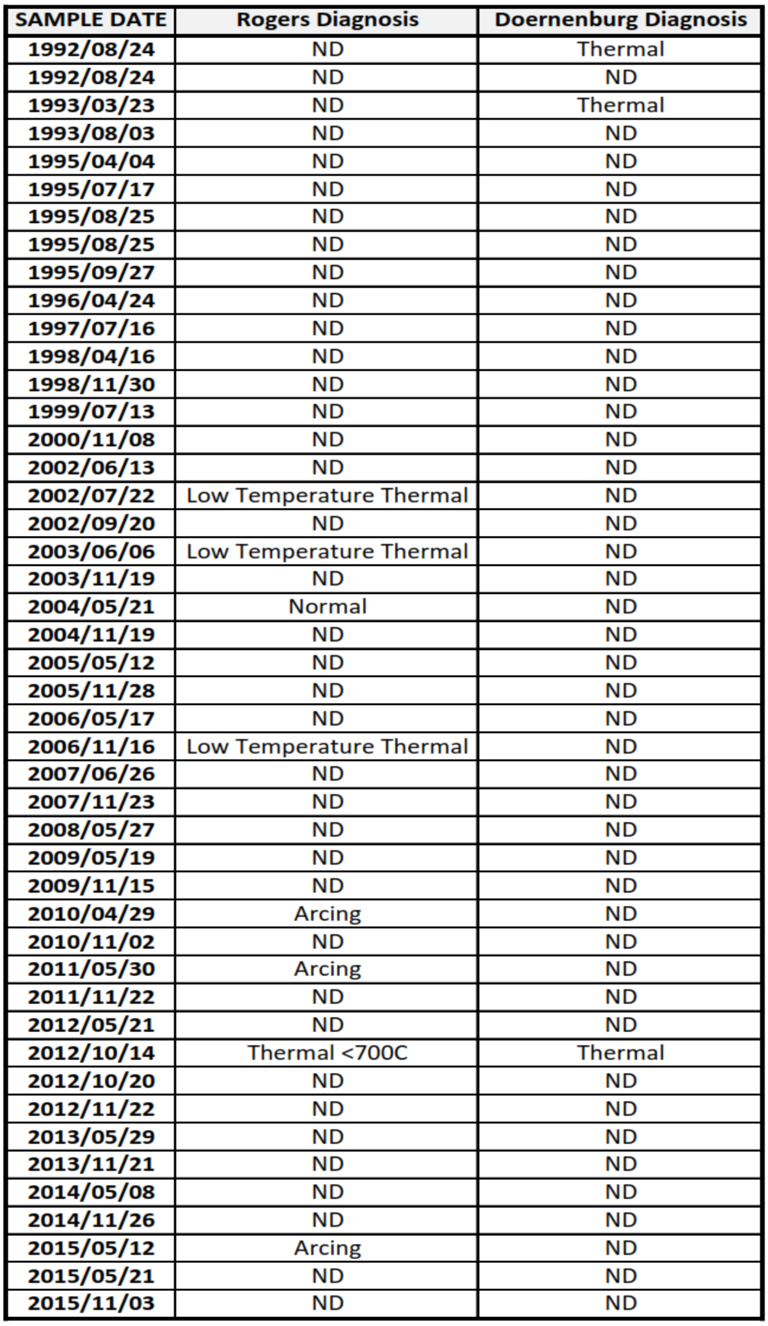


Figure 4-63: Case Study G - Combustible Gas Trend

4.7.3 Case Study G - Rogers and Doernenburg Ratio Methods

Roger’s and Doernenburg ratios were taken for the full sample range as indicated in Table 4-7. ND represents no diagnosis where Roger’s method had 78% and Doernenburg method had 85% ND diagnosis. Roger’s ratio method however did identify low temperature thermal fault in 2002-3 and arcing in 2011,2012 and 2015.

Table 4-7: Case Study G - Rogers and Doernenburg Diagnosis



SAMPLE DATE	Rogers Diagnosis	Doernenburg Diagnosis
1992/08/24	ND	Thermal
1992/08/24	ND	ND
1993/03/23	ND	Thermal
1993/08/03	ND	ND
1995/04/04	ND	ND
1995/07/17	ND	ND
1995/08/25	ND	ND
1995/08/25	ND	ND
1995/09/27	ND	ND
1996/04/24	ND	ND
1997/07/16	ND	ND
1998/04/16	ND	ND
1998/11/30	ND	ND
1999/07/13	ND	ND
2000/11/08	ND	ND
2002/06/13	ND	ND
2002/07/22	Low Temperature Thermal	ND
2002/09/20	ND	ND
2003/06/06	Low Temperature Thermal	ND
2003/11/19	ND	ND
2004/05/21	Normal	ND
2004/11/19	ND	ND
2005/05/12	ND	ND
2005/11/28	ND	ND
2006/05/17	ND	ND
2006/11/16	Low Temperature Thermal	ND
2007/06/26	ND	ND
2007/11/23	ND	ND
2008/05/27	ND	ND
2009/05/19	ND	ND
2009/11/15	ND	ND
2010/04/29	Arcing	ND
2010/11/02	ND	ND
2011/05/30	Arcing	ND
2011/11/22	ND	ND
2012/05/21	ND	ND
2012/10/14	Thermal <700C	Thermal
2012/10/20	ND	ND
2012/11/22	ND	ND
2013/05/29	ND	ND
2013/11/21	ND	ND
2014/05/08	ND	ND
2014/11/26	ND	ND
2015/05/12	Arcing	ND
2015/05/21	ND	ND
2015/11/03	ND	ND

4.7.4 Case Study G - Duval’s Triangle 1 Method

The Duval’s Triangle 1 method as indicated in Figure 4-64 was started off with thermal heating and picked up the event in 1997-99 which resulted in D2 discharges and the event in 2018-19 which was thermal related. The combustible gases were trending towards DT and T3 regions which is indicative of thermal and electrical faults greater than 700°C meaning that there was arcing at high energy discharge in the transformer.

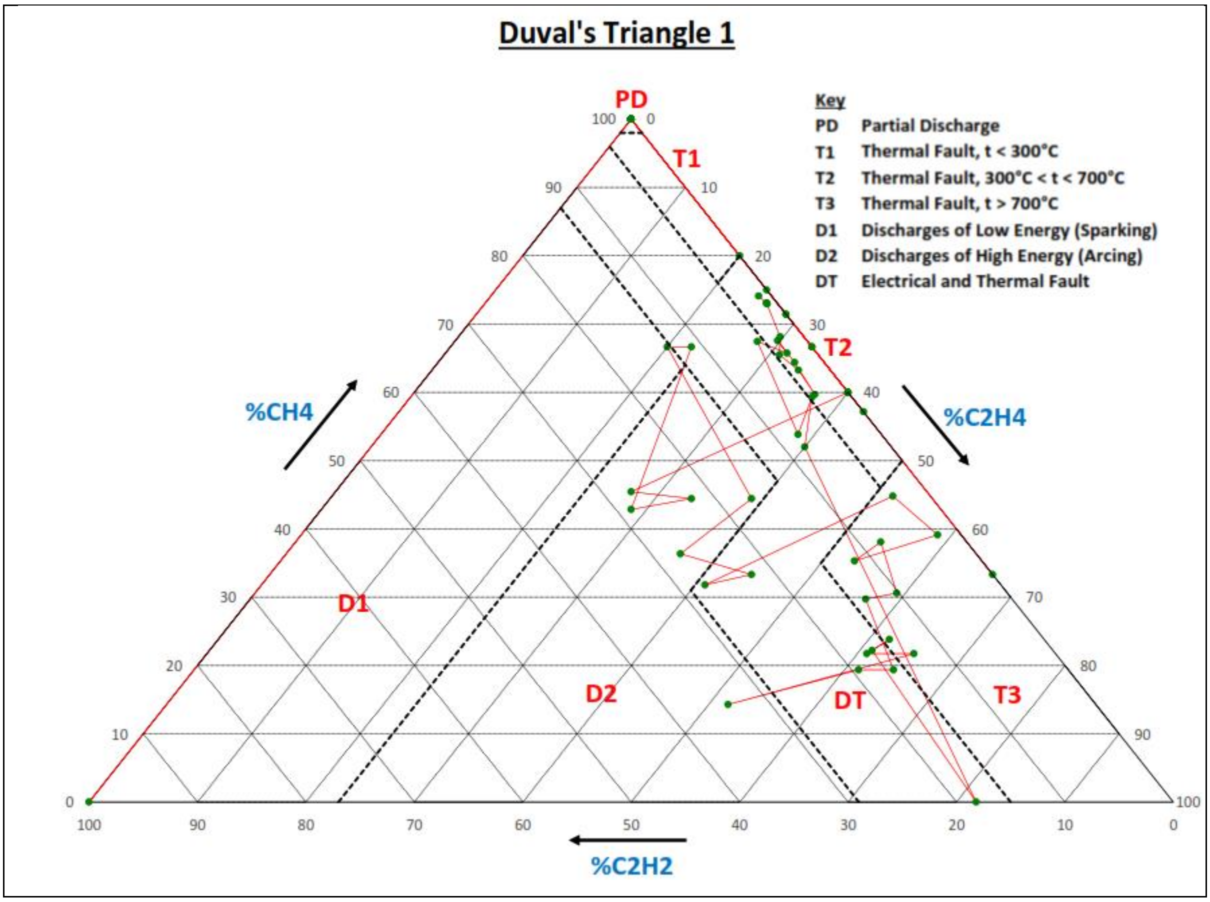


Figure 4-64: Duval's Triangle 1 Period 1 and 2

4.7.5 Case Study G - Duval's Pentagon 1 Method

The Duval's Pentagon 1 method depicted in Figure 4-65 indicated the condition from T1, T2, T3 and D1 and D2 discharges. This suggests that the fault progressing started form a thermal fault which started to get worst before the start of discharges until final failure.

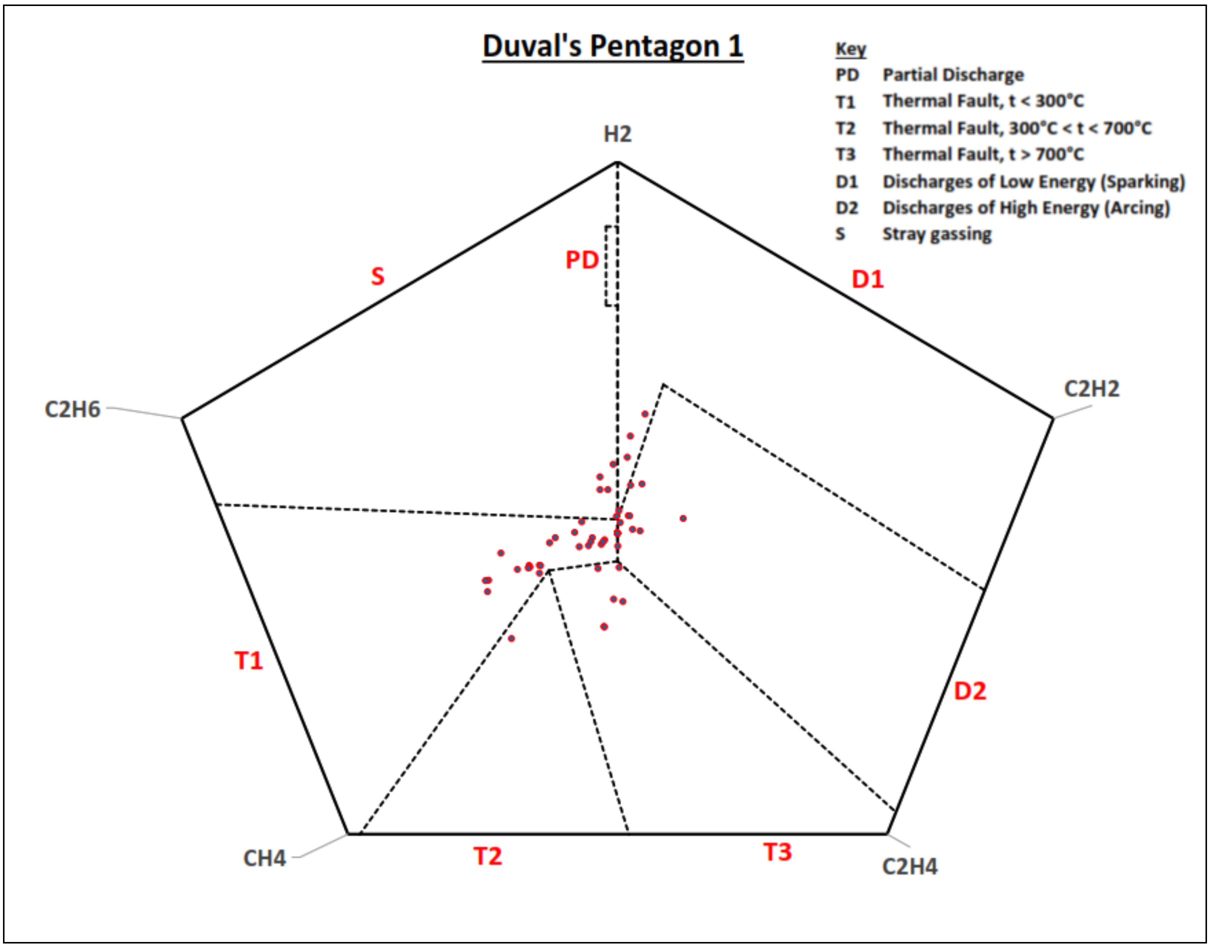


Figure 4-65: Case Study G - Duval's Pentagon 1 diagnosis

4.7.6 Case Study G - LEDT and R-Value Trend

The LEDT indicated that the problem started as early as 1996 when hydrogen (H_2) and methane (CH_4) spiked up. The escalation of the fault gases caused the transformer to be taken out from the network in September 2018. By this time the LEDT has indicated that there were D2 level discharges and T2 thermal fault.

From the LEDT in Figure 4-66 most of the samples were in the normal region from 1992 to 2017 but in the years 1997 to 1999 there seems to be an event that resulted in thermal heating which took the samples into the T1 and T2 regions. The transformer samples fluctuated around the normal region until 2018 when there was a significant discharge of type D2 which then progress to a T2 fault between Oct-Dec 2018 and further into the T2 region in Jan-Mar 2019 until it was taken out of service.

An in-tank investigation was undertaken in 2018 where a defect was observed. When the transformer was put back to service, all the combustible gases started increasing at the low scale where R-Value confirm the spike occurred in 2011 and 2012 and subsided the fault to normal region. The defect caused the transformer to fail, it is obvious that is defect was confirmed by LEDT during Period 1.

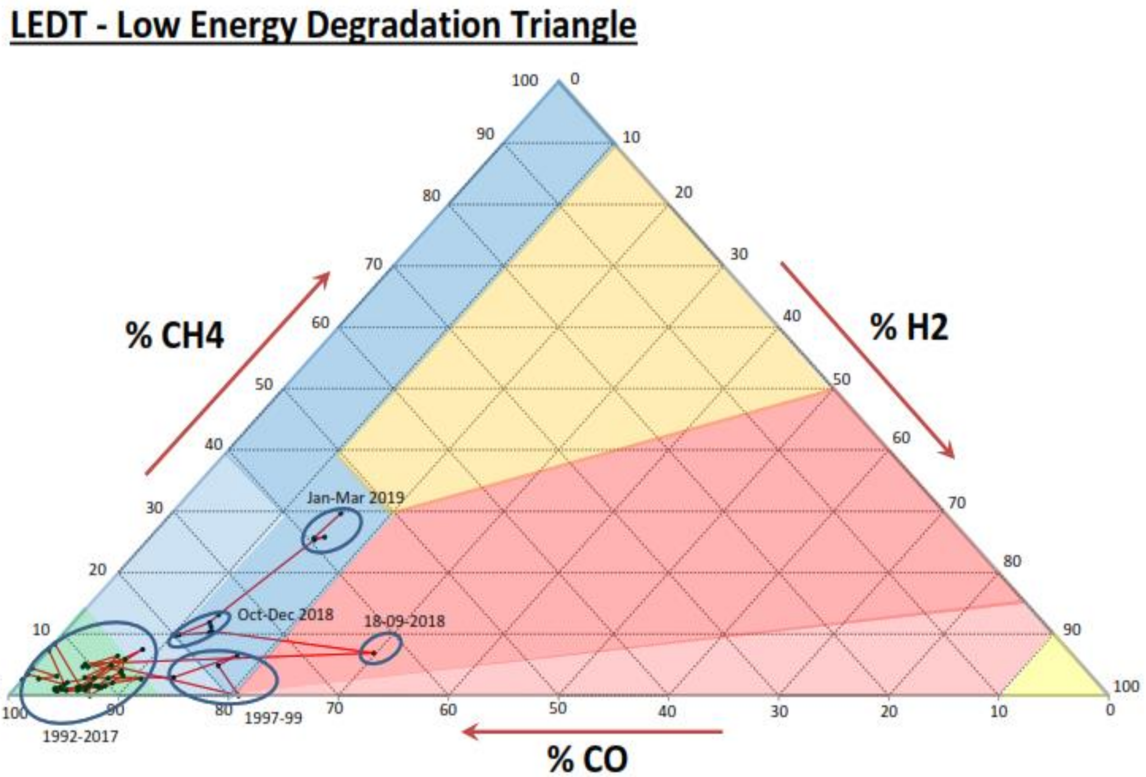


Figure 4-66: Case Study G - LEDT

The R-value trend from Figure 4-67 supports the LEDT trend and it clearly indicates the a few significant events. The first one started on 1994, then in 2002, 2008, 2010-11 and the final event in 2018.

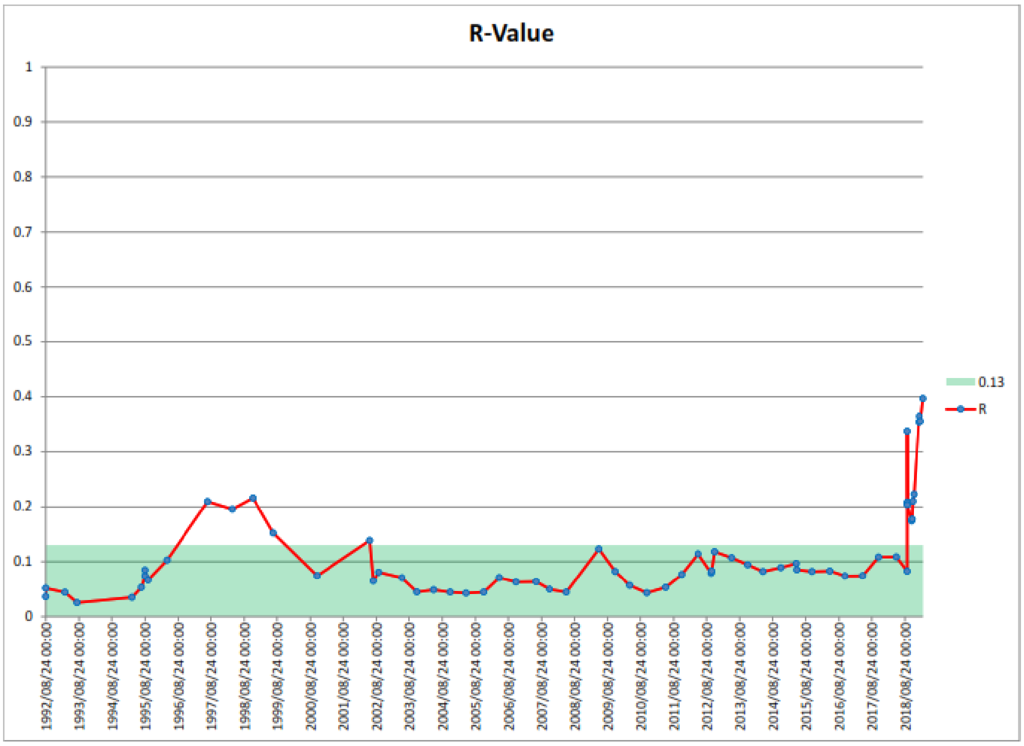


Figure 4-67: Case Study G - R-Value

4.7.7 Case Study G - Extension of MEDT

MEDT and R-Value Trend

Both the MEDT and R-Value trend in Figure 4-68 also provides some alignment to the LEDT method. In this case it shows a direct movement from the normal region into the abnormal region with the start of the increasing trend from 2002.

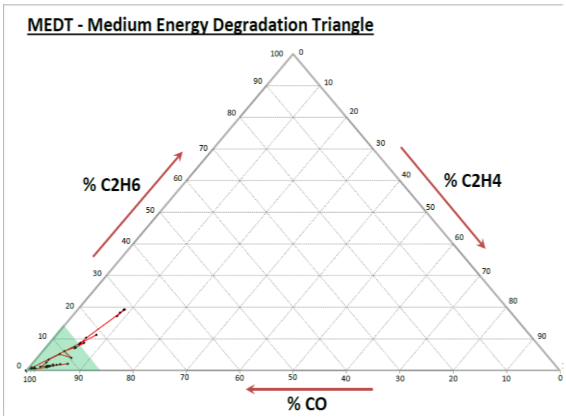
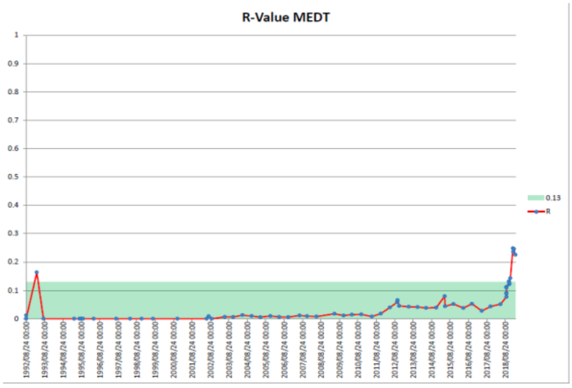
MEDT Period 2	R-Value
	

Figure 4-68: Case Study G - MEDT and R-Value Period 1

4.7.8 Case Study G: Evaluation

From the internal inspection conducted in the transmission substation there was evidence of severe overheating on the 400kV HV lead and burnt paper insulation on the HV lead joints were observed. See the damaged component in Figure 4-69.

Figure 4-69: Centre fed lead (400 kV)

One explanation for the low gassing levels, considering the type of fault, was because the lead was heavily insulated with paper which may have restricted the gas diffusion into the oil. Another possible reason the hydrocarbons remained low is the fact that there was not much mineral oil to burn around the lead, except the tiny film between the first layer of paper and the copper body and the one absorbed in the paper.

LEDT Method was able to identify increasing fault trends from the normal zone to low thermal fault T1 to medium thermal fault T2 in 1997-99. In October 2018 the fault moved from T2 high energy Discharge D2 and in Jan – Sept 2018 and back to T2 thermal fault in Jan- Mar 2019 with the final failure.

Duval’s Triangle 1 indicated three high thermal gas fault T3 zone and two DT results which is transition zone for thermal and electrical fault. Duval’s Pentagon 1 indicated all fault zones from T1, T2, T3 to high energy discharge fault zone.

The root cause of the failure was thermal fault caused by a bad HV lead joint with transition to an electrical discharge fault.

5 Discussion of the Case Studies

This study presented seven case studies of transformers within the transmission network that have either failed or was taken out of service due to gassing. The main objective of the case studies was to test the accuracy and consistency of diagnoses of a detected incipient fault in the mineral oil-filled transformers and reactors.

Based on the case study findings, it was clear that all DGA diagnostic methods were able to identify faults in the transformers even though with different accuracy and consistency. Table 5-1 provides a summary of the case studies in terms of the percentage samples that were able to provide a diagnosis.

The Rogers and the Doernenburg ratios had many no-diagnosis results. According to the standards C57.104 and IEC 60599, low ratios and gas levels below limit values represent a healthy condition of no concern, but norms have been established from data with wide ranges. The LEDT on the other hand, which represents a more complex gas ratio, has been shown to indicate the start of a trend away from a healthy condition at an earlier stage of degradation with much lower combustible gas concentrations. The threshold of the healthy condition is based on analysis of the Eskom fleet of transformers.

Table 5-1: Percentage of Sample Diagnosis

Case No	Roger's	Doernenburg	Duval's Triangle	Duval's Pentagon	LEDT	MEDT
A	65	45	100	100	100	100
B	33	23	100	100	100	100
C	26	74	100	100	100	100
D	6	76	100	100	100	100
E	2	78	100	100	100	100
F	67	48	100	100	100	100
G	22	15	100	100	100	100

Due to the nature of the Duval’s triangle 1 and pentagon 1 all areas provide a diagnosis of fault type. However, neither method identifies areas of normal operation. The Duval’s triangle 1 and pentagon 1 show degradation of oil or decomposition of cellulose that together indicate the type of fault that occurred. Furthermore, these methods sometimes differ in the early diagnosis of a fault, because in some cases

Duval’s Triangle 1 started to diagnose the fault as at the thermal stage and Duval’s Pentagon 1 started diagnosing the fault at the partial discharge stage.

The LEDT and MEDT methods both offer a diagnosis of fault typebut are also able to indicate a normal operation region which can be effectively used for fleet management of a transformers with the focus given only to transformers that needing attention. This saves the transformer engineer a lot of time especially when managing a large fleet of power transformers.

The LEDT and MEDT in case studies A, B, C, D indicated that they started from T1 from the earliest DGA monitoring and showed the trend of degradation. Case studies E, F and G indicated when their fault started to generate at the normal region. The R-Value complements the diagnostic results.

Table 5-2 provides a summary of the seven methods evaluated. The first criterion evaluated was if the method can confirm the normal operating state of the transformer without any incipient faults. In this case only the Rogers Ratio, LEDT and MEDT methods were able to satisfy this criterion. This was one of the main requirements of the condition monitoring assessment tool; the ability to be able to show a change in state from normal/healthy to abnormal/unhealthy.

Table 5-2:Summary of Case Studies

No	Analysis Method	Identify Normal State	Identify Type of Fault	Provide Visual Trend of fault progression	Have a minimum Criteria before using
1	Rogers Ratio	Yes	Yes	No	Yes
2	Doernenburg Ratio	No	Yes	No	Yes
3	Combustible Gas Trend	No	No	Yes	No
4	Duval's Triangle	No	Yes	No	Yes
5	Duval's Pentagon	No	Yes	No	No
6	LEDT and R-Value	Yes	Yes	Yes	No
7	MEDT and R-Value	Yes	No	Yes	No

It is also useful to have a diagnosis of the type of fault. The Rogers, Doernenburg, Duval’s Triangle 1 and Pentagon 1 and LEDT methods were able to identify the type of fault. However, except for the Pentagon, their use depends on a threshold of gas ratio or concentration being exceeded.

The MEDT at present is not able to identify the type of fault as this is a new method and the fault regions must be still identified. With further research in this area this gap can be filled. Identifying the type of fault is important in identifying the possible location of the fault which will tremendously assist in fault finding failures in power transformers.

Another important function of a condition monitoring tool is to be able to easily identify the fault progression within a power transformer so that repairs can be effectively planned before a failure occurs and to also be able to get maximum output from the assets. This holds especially true in the current constrained electricity utility environment. The methods that was able to effectively meet this criterion were the Combustible Gas trend, LEDT and MEDT methods and showed the accuracy of status of the fault. The LEDT and MEDT makes use of the R-Value trend which provides a clear visual trend of the progression of the fault over time. Both the Duval’s Triangle 1 and Pentagon 1 can provide some trend, but this is not easily visible over time.

Another limitation of diagnosis methods is that an initial criterion must be first met before the method can be used for diagnosing. This is evident on the Doernenburg method where significant levels of gases must be present before a diagnosis is valid. Although the Rogers ratio does not require specific gas concentrations it is suggested that it be used only when the normal gas limits are exceeded. This also holds true for the Duval’s Triangle 1 and Pentagon 1 since all points in the triangle and pentagon indicate a fault and the diagnosis should only be applied when the combustible gas limits have been exceeded.

Table 5-3 provides an assessment of the ability of the LEDT to identify faults early – before failure or being taken out of service. For all the case studies presented it was identified that the LEDT and R-value trend was able to identify the initial incipient fault years before failure occurred. The R-value is a simple single indicator of the rate of increasing degradation, almost independent of the variability of the combustible gas trends.

The masking effect of high levels of CO in the case study F draws attention to a proposal [Moodley 2017] to limit the base values of CO in the LEDT to 500 ppm or even 350 ppm.

Table 5-3: Summary of Case Study – LEDT Fault Identification Period

Case No	Fault Type	Date of first Trigger	Date of Failure / Taken Out	Period before failure
A	Thermal overheating	2010/11/24	2013/05/24	2 Years 6 months
B	Thermal overheating	1997/11/28	2018/02/18	20 Years 3 months
C	Disharges and Thermal Overheating	2002/02/27	2010/06/21	8 Years 4 months
D	Winding Interturn fault	2005/01/07	2017/10/01	12 Years 9 months
E	Disharges and Thermal Overheating - short lamination and loose connection	2004/06/22	2018/07/17	14 Years 1 months
F	Arcing due to insulation deterioration	2013/05/16	2018/04/27	4 Years 11 months
G	Thermal overheating hot spot on HV leads	1997/07/16	2019/03/14	21 Years 8 months

It was also identified that the initial normal state correlated with the LEDT normal region, and a defective trigger was consistent with the LEDT fault regions. It was identified that even though the combustible gas trends were erratic the LEDT was relatively insensitive to these changes.

Based on all case study findings, all the DGA methods or representing an incipient fault developing in mineral oil-filled transformers/reactors were capable in identifying a fault, but not all methods were able to indicate progression from a normal or healthy state.

From the case studies it is identified that the LEDT and MEDT offered the advantage of identifying the normal state or healthy of a power transformer internal condition and its movement into the abnormal state by its R-Value. This is advantageous for fleet management of transformers.

The Duval's Triangle 1 and Pentagon 1 also play an important role in identifying the types of faults, especially for higher energy faults and can be used as a check of the fault-type diagnosis of the LEDT and MEDT.

Based on the findings, it is useful to consider what underlies the differences between the various methods of interpreting the DGA results. The LEDT is less sensitive to the quantity of gas than it is to the composition of the gas, which is taken as an indicator of the intensity of the degradation. This suggests that intensity or the relative rates of gas formation and accumulation is related to the fault inception and increasing degradation.

LEDT picks up early warning of $CH4$ or $H2$ formation. Slow generation of $H2$ or $CH4$ is balanced by CO, until one of the gases starts to "go out of control", and before the threshold criteria of the Duval Triangle is reached. The Duval Triangle can be used to identify the fault type after a fault condition is identified by the threshold of gas quantities or ratio criteria.

The threshold of relevance of the Duval Pentagon 1 is unclear because it lacks a stabilising parameter like the CO of the LEDT.

When CO levels are consistently high, and mask the generation of combustible gases, the LEDT may not be sufficiently sensitive. This can be addressed by capping the level of CO concentration applied to the LEDT plot.

6 Chapter 6: Dissolved Gas Analysis of Ester Transformer Oil

6.1 Introduction

This chapter uses laboratory generated experimental data obtained from literature which is of clearly defined gas generation set-ups. These experimental set ups attempt to simulate the conditions generally referred to as “thermal”, “partial discharges” and “low energy discharges” commonly referred to in the DGA industry. This is done for mineral oil, natural ester oil and synthetic ester oil. The data is plotted in the LEDT, MEDT and Duval’s Triangle 1 methods where some conclusions are drawn.

Chapters 3 and 4 examined the results of the different methods of interpreting the levels of dissolved gasses in mineral oil with the diagnosing consistency of the techniques. From the methods evaluated for accuracy, the ability to give an early indication of an abnormality, to represent the trend of the degradation and to identify the dominant type of degradation it was found that the simple ratios (Doernenburg and Rogers Ratio method) were ineffective. The Duval’s Triangle 1, Duval’s Pentagon together with the LEDT methods were found to provide positive results in this regard thus only these methods will be investigated on non-mineral oils.

This chapter evaluates the relevance of the Duval’s Triangle 1 and LEDT methods to interpreting the degradation in non-mineral oil-filled transformers. The information used to test the validity were extracted from the published paper researched with results present in Table 6.1 and 6.2 [Imad-U-Khan 2007].

6.2 Non-Mineral Oil

Both synthetic and natural ester oils have drawn attention worldwide for their “sustainable” properties as substitutes for mineral oil [Rafiq 2015]. Ester oil offer the advantages of being environmentally friendly, having high fire resistance and low viscosity [Mahanta 2020]. A study found that ester oils had voltage properties to withstand high stresses that was comparable with mineral oil [Azcarraga 2014].

The ester oils and mineral oil differ in chemical composition structures [Singha 2014]. Like mineral oils, the fault gases developed in the liquid immersed transformers can be divided into three degradation processes arising from partial discharges, arcing, and thermal stress, and producing different compositions of dissolved gases [DiGiorgio 2005].

6.3 The Diagnosis Methods tested on Ester Fluids

There is little information about interpreting the dissolved gas analysis in ester oils [Hamid 2017]. Numerous experiments have been conducted to investigate if DGA could be used as a tool to diagnose faults generated in ester filled transformers. Faults in ester oil, discharge, and overheating, usually generate the same five key gases as degradation in mineral oil [Wang 2002] [Jovalekic 2009]. Thermal faults in ester liquids generate larger quantities of combustible gases than in mineral oil-filled transformer [Przybylek 2019]. Comparison indicated that ethane (C_2H_6) was generated at a high rate by thermal decomposition in the natural ester oil without developing into a fault. The cause of the high ethane production is that it generally has unsaturated bonds, and it contains a linolenic acid that produces ethane as a by-product [Jovalekic 2009]. It appears, therefore, that high ethane levels in natural esters relative to those in mineral oil may not be an indicator of incipient failure but might increase fire risk.

6.4 Thermal Tests in oil only at 90°C, 150°C and 200°C

The study done on three liquid insulations compared the concentration of the fault gases of Midel 7131 synthetic ester, FR3 natural ester, and mineral oil all of which included that of Kraft paper insulation [Imad-U-Khan 2007].

Tests were conducted on the three types of oil only at 90°C, 150°C and 200°C under different time frames. The results are presented in Table 6-1. It was found that Midel 7131 generated the least fault gases with FR3 generating a significant amount of hydrogen and ethane. At 90°C it was identified that ethylene was not produced by the ester oils with only 1 ppm in mineral oil. This was an expected result as ethylene is usually associated with high energy thermal faults.

Table 6-1: Dissolved Gas (ppm) - Thermal in oil only (90°C and 150°C for 3 and 14 days, at 200°C for 1 hour) [Imad-U-Khan 2007]

Oil Type	Mineral Oil						Synthetic Ester (Midel)						Natural Ester (FR3)					
Test Temp	90°C			150°C		200°C	90°C			150°C		200°C	90°C			150°C		200°C
Test Time	c	3d	14d	3d	14d	1h	c	3d	14d	3d	14d	1h	c	3d	14d	3d	14d	1h
H_2	5	16	28	14	16	21	7	9	7	14	14	8	8	64	253	59	19	17
CH_4	1	2	4	48	194	95	0	1	1	7	40	16	1	1	4	7	23	7
C_2H_6	0	1	2	28	125	48	0	1	0	2	49	4	2	18	103	88	179	177
C_2H_4	1	1	1	7	14	9	1	0	1	3	34	3	1	0	1	5	16	4
C_2H_2	1	0	1	0	0	5	0	0	0	0	0	0	6	0	0	0	0	0
CO	18	25	98	262	592	148	9	17	60	152	533	74	6	16	53	171	540	68
CO_2	73	165	502	1976	3354	1006	111	89	283	1073	3514	521	82	129	430	1586	5359	914
TDCG	26	45	144	359	941	326	17	28	69	177	670	102	24	98	414	330	177	273

6.4.1 90°C for 14 days

The results of the LEDT and Duval's Triangle 1 method are presented in Figure 6-1 where the analysis was plotted for the 14-day period.

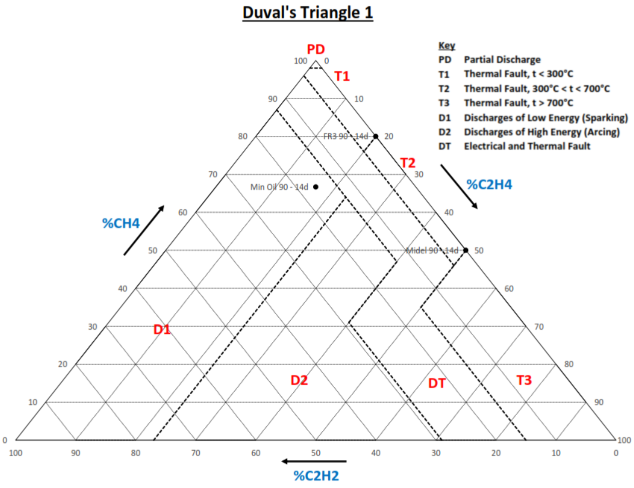
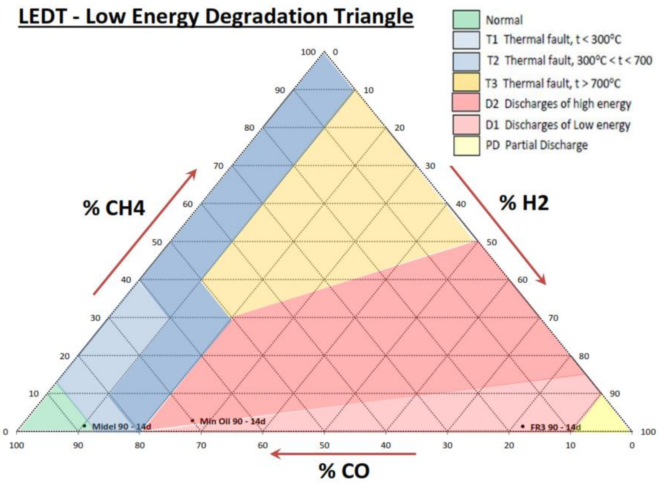
Duval's Triangle 1	Low Energy Degradation Triangle
	

Figure 6-1: Duval's Triangle 1 and LEDT – Thermal in oil (90°C – 14d)

For the LEDT method the mineral oil at 90°C it was found that the14-day was in the D2 region. For Midel 7131 at 90°C the 14-day sample was in upper limits of the Normal region. This was due to the higher CO levels generated when compared to H_2 and CH_4. For FR3 at 90°C the 14-day sample was in the D1 region closer to the PD region.

For the Duval’s Triangle 1 the mineral oil at 90°C 14-day sample was in the D1 region.

For Midel 7131 at 90°C the 14-day sample was in the border of the T2 and T3 region. For FR3 at 90°C the 14-day sample was in the border of the T1 and T2 region.

6.4.2 150°C for 14 days

The results of the LEDT and Duval’s Triangle 1 method are presented in Figure 6-2 where the analysis was plotted for the 150°C at the 14-day period.

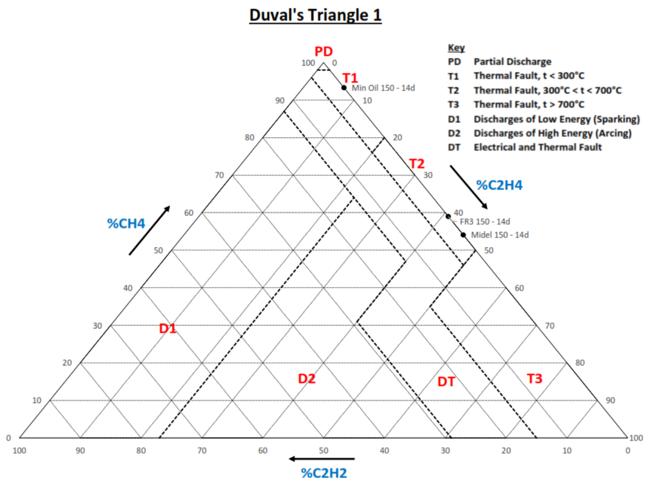
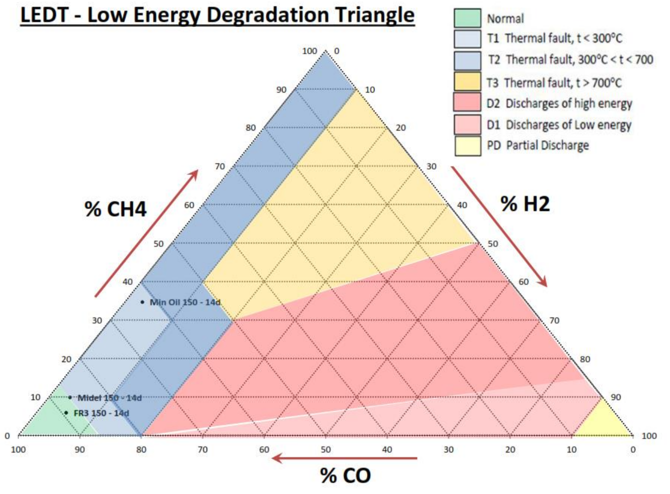
Duval’s Triangle 1	Low Energy Degradation Triangle
	

Figure 6-2: Duval’s Triangle 1 and LEDT – Thermal in oil (150°C – 14d)

For the LEDT method the mineral oil at 150°C it was found that the sample point was in the T1 region. For Midel 7131 at 150°C the 14-day sample was in upper limits of the Normal region. This was due to the higher CO levels generated when compared to H_2 and CH_4. For FR3 at 150°C the 14-day sample was in the normal region.

For the Duval’s Triangle 1 the mineral oil at 150°C 14-day sample was in the T1 region. For Midel 7131 and FR3 at 150°C the 14-day sample was in the T2 region.

6.4.3 200°C for 1 hour

The results of the LEDT and Duval's Triangle 1 method are presented in Figure 6-3 where the analysis was plotted for the 14-day period.

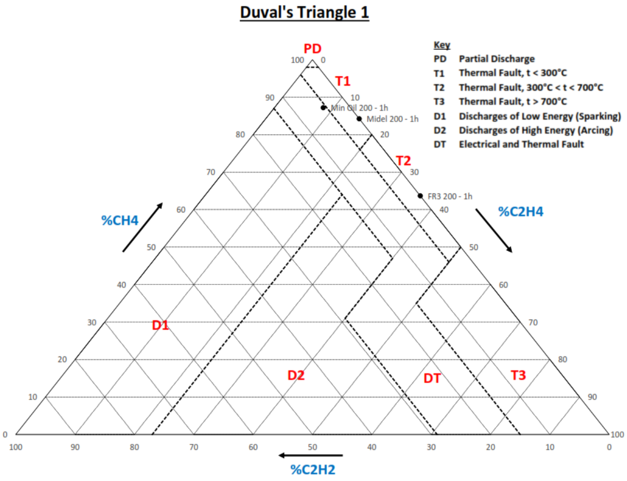
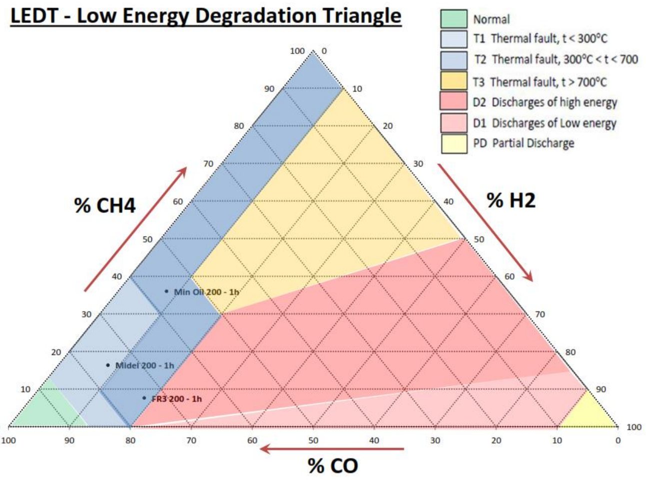
Duval's Triangle 1	Low Energy Degradation Triangle
	

Figure 6-3: Duval's Triangle 1 and LEDT – Thermal in oil (200°C – 1 hour)

For the LEDT method the mineral oil at 200°C it was found that the sample point was in the T2 region. For Midel 7131 at 200°C the 14-day sample was in T1 region. For FR3 at 200°C the 14-day sample was in the T2 region.

For the Duval's Triangle 1 the mineral oil at 200°C 14-day sample was in the DT region. For Midel 7131 it was in the T1 region and FR3 at 200°C the 14-day sample was in the T2 region.

6.5 Thermal Tests in Oil and Paper 150°C and 200°C

Table 6-2 provides the results of the combustible gases from mineral oil, Midel 7131 and FR3 in the presence of Kraft paper which was taken over a period of 14 days at 150°C and 1 hour at 200°C.

It is found that the presence of paper insulation has resulted in the increase in the concentration of carbon monoxide and carbon dioxide for the temperature at 90°C and 150°C. It is also identified that the concentration of CO and CO_2 are highest in mineral oil then Midel 7131 and FR3 respectively.

Table 6-2: Dissolved Gas (ppm) - Thermal in oil/paper (90°C, 150°C and 200°C) [Imad-U-Khan 2007**]**

Oil Type	Mineral Oil				Synthetic Ester (Midel)				Natural Ester (FR3)			
Test Temp	**Control**	**90°C**	**150°C**	**200°C**	**Control**	**90°C**	**150°C**	**200C°**	**Control**	**90C°**	**150C°**	**200°C**
H_2	8	46	34	19	7	13	24	14	8	244	26	23
CH_4	1	10	259	90	1	3	40	15	1	6	31	10
C_2H_6	0	2	187	43	1	0	33	4	1	116	179	171
C_2H_4	1	2	25	5	1	1	16	4	1	2	19	7
C_2H_2	1	1	1	0	1	1	0	1	1	0	0	1
CO	6	590	9187	890	5	307	3815	541	6	88	5472	1330
CO_2	108	3407	101167	19603	45	2212	56508	9524	82	1354	60675	18717
TDCG	17	654	9693	997	16	325	3928	579	18	456	5727	1542

6.5.1 Thermal in Oil/Paper at 150°C

The results of the Duval's Triangle 1 and LEDT method are presented in Figure 6-4 for 150°C.

Duval's Triangle 1	Low Energy Degradation Triangle

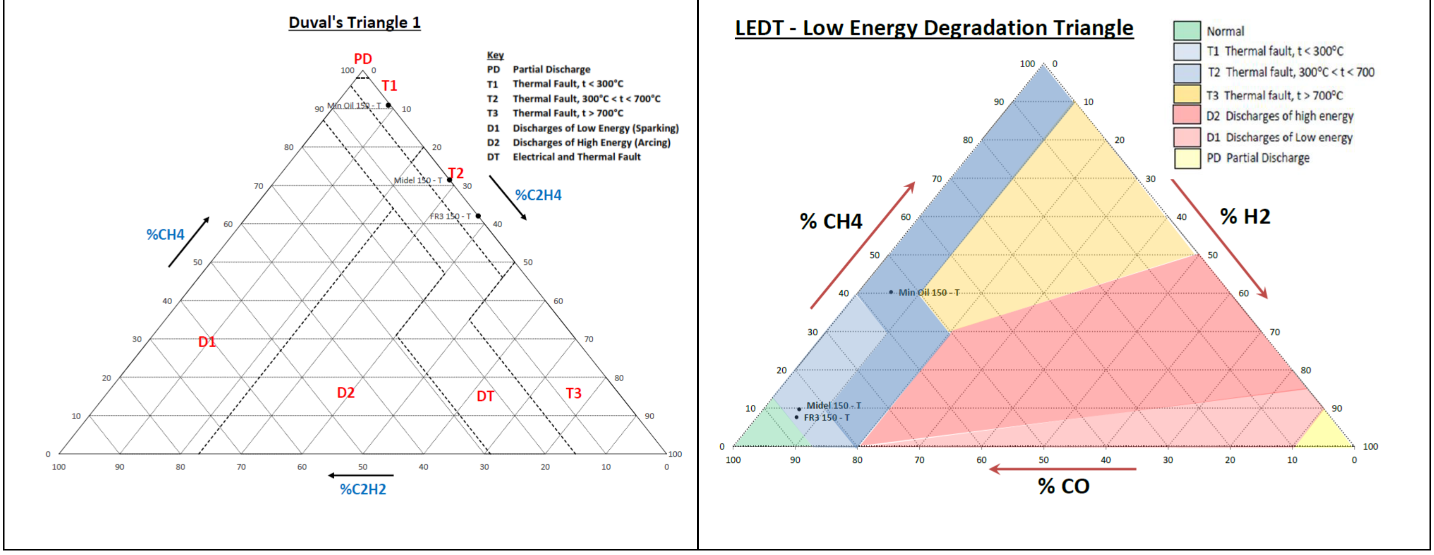


Figure 6-4: Duval's Triangle 1 and LEDT - Thermal Tests in Oil & Paper at 150°C

The LEDT method for mineral oil at 150°C it was indicated in the T2. For synthetic ester (Midel 7131) and FR3 at 150°C sample was plotted in the T1 region.

The Duval's Triangle for mineral oil at 150°C was in the T1 region and both Synthetic ester oil (Midel 7131) and FR3 was in the T2 region.

6.5.2 Thermal in Oil/Paper at 200°C

The results of the Duval's Triangle 1 and LEDT are presented in Figure 6-5 for thermal in oil and paper at 200°C.

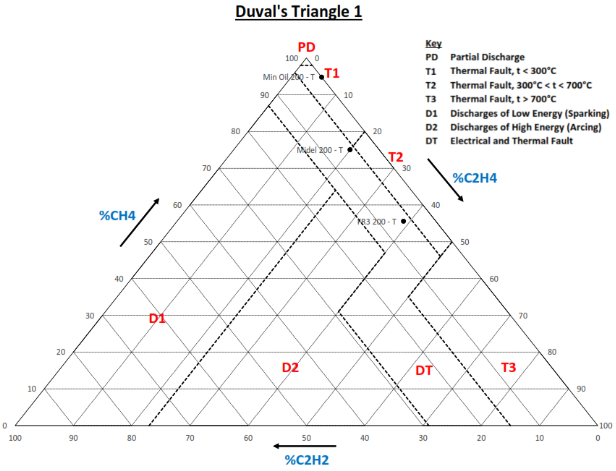
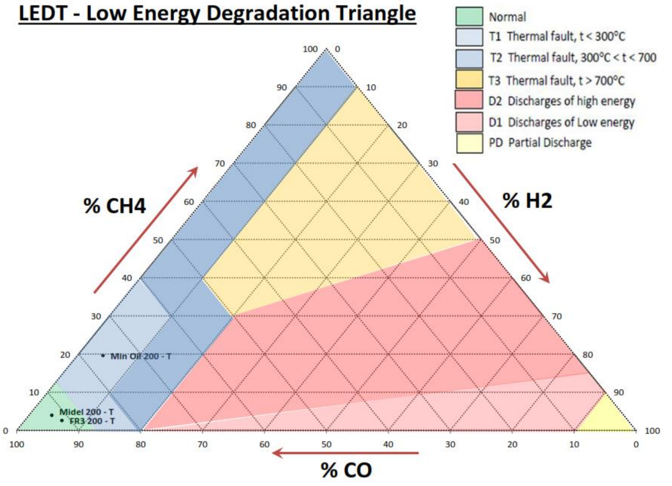
Duval's Triangle 1	Low Energy Degradation Triangle
	

Figure 6-5: Duval's Triangle and LEDT – Thermal test in oil and paper at 200°C

For the LEDT method the mineral oil at 200°C it was found that the sample point was in the T2 region. For both Midel 7131 and FR3 at 200°C the samples were in normal region.

For the Duval's Triangle 1 the mineral oil at 200°C was in the T1 region. For Midel 7131 and FR3 it was in the DT region.

6.6 Partial and Low Energy Discharge

Table 6-3 provides the results from the partial discharge tests conducted on the three insulating oils [Imad-U-Khan 2007]. Two types of discharges were tested: that of low energy arc discharge and corona type discharge. Analysis of these results are provided below.

Table 6-3: PD and Low Energy Discharge

Oil Type	**Mineral Oil**			**Synthetic ester**			**Natural ester**		
Sample	**C**	**LEDT**	**CDT**	**C**	**LEDT**	**CDT**	**C**	**LEDT**	**CDT**
H_2	5	901	20	7	97	5	8	191	23
CH_4	1	145	2	0	9	2	1	14	2
C_2H_6	0	24	0	0	2	0	2	10	1
C2H4	1	270	2	1	26	0	1	63	2
C_2H_2	1	1540	2	0	126	0	6	289	2
CO	18	6	2	9	37	2	6	51	8
TDCG	26	2886	28	17	297	9	24	609	38

C: Control samples
LEDT: Low energy arc-discharge test
CDT: Corona type discharge test.

Figure 6-6 provides the representation of the samples for PD and Low Energy Discharge on the LEDT and Duval's Triangle 1 method.

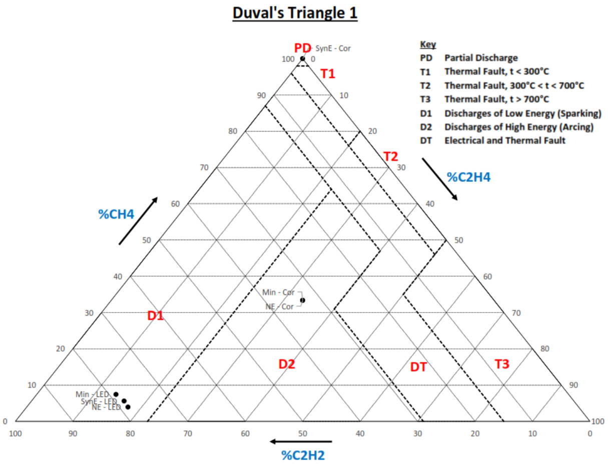
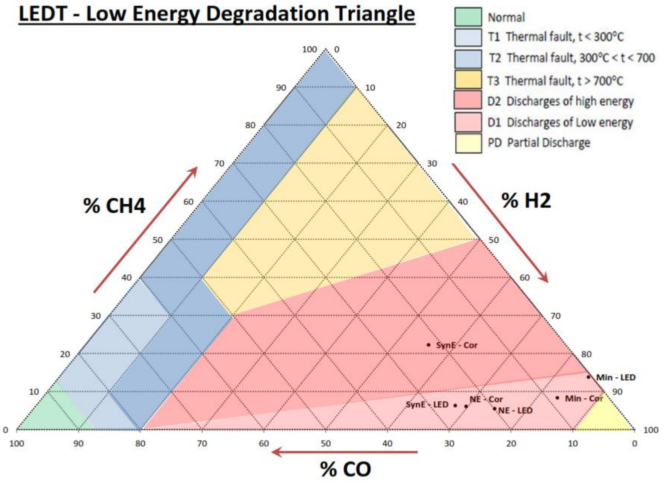
Duval’s Triangle 1	Low Energy Degradation Triangle
	

Figure 6-6: Duval’s Triangle 1 and LEDT - PD and Low Energy Discharge (200°C – 1 hour)

For mineral and natural ester oil both low energy and corona discharge are found in the D1 region.

For synthetic ester the low energy discharge sample was in the D1 region, and the corona discharge sample was in the D2 region. For Natural Ester both the low energy discharge and corona was in the D1 region.

The Duval’s Triangle 1 analysis for mineral oil, natural ester and synthetic ester the low energy discharge samples were indicated in the D1 region. For mineral oil and natural ester, the corona discharge was indicated in the D2 region. For synthetic ester the corona discharge sample was in the PD region.

6.7 Discussion and Conclusion

Although the molecular structures of natural and synthetic esters are different from that of mineral oil [Singha 2014] (Martin, et al., 2016). it is found that there are some similarities between the gasses generated for thermal and electrical faults.

It is also found that the rate of generation of dissolved gases in esters is less in comparison with mineral oil [Imad-U-Khan 2007]. FR3 is found to generate significant amounts of ethane for thermal faults, and it is identified that carbon monoxide and carbion dioxide are produced at higher rates than for mineral oil.

The following table is the summary of the diagnosis between the LEDT and Duval's Triangle 1 method.

	LEDT	Duval's Triangle 1
90°C for 14 days		
Mineral Oil	D2	D1
Midel 7131	Normal	T1/T2
FR3	D1	T2/T3
150°C for 14 days		
Mineral Oil	T1	T1
Midel 7131	T1	T2
FR3	Normal	T2
200°C for 1 hour		
Mineral Oil	T2	DT
Midel 7131	T1	T1
FR3	T2	T2
Thermal in Oil/Paper at 150°C		
Mineral Oil	T2	T1
Midel 7131	T1	T2
FR3	T1	T2
Thermal in Oil/Paper at 200°C		
Mineral Oil	T1	T1

Midel 7131	Normal	DT
FR3	Normal	DT
Low Energy Discharge		
Mineral Oil	D1	D1
Midel 7131	D1	D1
FR3	D1	D1
Corona		
Mineral Oil	D1	D2
Midel 7131	D2	D1
FR3	D1	D2

For thermal degradation in oil there was some corelation in the diagnosis between the LEDT and the Duval’s Triangle 1. The higher levels of CO also caused some samples in the LEDT to have less impact in terms of the fault level.

For thermal degradation of paper there was some correlation between the LEDT and Duval’s triangle 1. The LEDT however tended to identify some of the samples as higher energy T3 and D2 faults as opposed to the Duval’s T2 faults.

For discharges of low energy there was good correlation between the LEDT and Duval’s Triangle 1.

Therefore, it can be concluded that both the Duval’s Triangle 1 and LEDT may provide some value in assessing the dissolved gas samples for faults within the power transformer.

The above quantitively analysis clearly suggests that, based on this set of data, the Duval’s Triangle 1 may have identified the primary cause of the gas formation for all three types of oil tested.

The LEDT method indicated “thermal” does not identify any condition corresponding to DT degradation which indicates the transition of a thermal to an electrical fault. Considering that the key advantage of the LEDT over other approaches is the ability to depict a trend in the degradation over time, the diagnosed fault type is inconclusive. It reflects the gas generation under different thermal conditions. Given the same paper for all the thermal tests of oil/paper, the gas generation is the result of the oil dissociation at that temperature.

Both the Duval Triangle and the LEDT indicate degradation by electrical discharge in thermal tests, which is an unlikely result. This inconsistency in the results suggests the type of mechanism that caused the gas generation may not be interpreted correctly. It leaves the maintenance engineer with little confidence with respect to what DGA interpretation reveals. Further work appears to be needed.

7 Chapter 7: Conclusion

7.1 Main objective

The main objective of this study was to validate the effectiveness of the LEDT method for diagnosing incipient faults in transmission type transformers. The LEDT method was already proven as a valuable tool in assessing the health of GSU transformers in a previous study [Moodley 2017]. Due to the low loading of transmission transformers, it was necessary to investigate the viability of the LEDT as an assessment tool in this regard.

To complete the assessment the LEDT was also compared with other diagnosis techniques such as Roger's Ratio, Doernenburg's Ratio, Duval's Triangle 1, Duval's Pentagon 1 and MEDT methods.

A supplementary investigation was also undertaken to assess the viability of the LEDT, MEDT and Duval's Triangle 1 method on non-mineral oil such as natural and synthetic esters.

7.2 Answering the Research Questions

The following research questions were answered to validate the hypothesis of the research.

What are the properties of the key dissolved gases that make the combination of their measurements meaningful for condition monitoring?

During normal operation and fault conditions dissolved gases are produced in the transformer. This is fundamentally due to the breakdown of the liquid insulation like mineral oil and solid cellulose insulation. These materials are made up of hydrocarbons and carbon oxides which form at different temperatures. This offers the advantage that by identifying the different types of gasses the related conclusions can be drawn on the type of energy is involved. It is identified that hydrogen, methane and carbon monoxide is produced at normal to low temperature faults. As the fault energy increases the significant dissolved gases produced is ethane with hydrogen. Further increase due to thermal energy results in ethylene being produced at a high volume. For high energy arcing there are significant amounts of acetylene and hydrogen produced.

There have also been numerous studies to identify the fault types to the corresponding dissolved gases. This study has also used the standard dissolved gas limits and trends for assessment of the seven case studies. The methods like the Duval's triangle 1, LEDT and MEDT have been based on the combination of dissolved gases to provide a single diagnosis based on the amounts of each gas generated at the different energy levels. It is thus identified that there is value offered by combining the different dissolved gases to assess the condition of the transformer internal condition.

Is the LEDT method and other methods such as Duval's Triangle 1, Rogers Ratio and Doernenburg effective in interpreting the dissolved gas results for transmission transformers filled with mineral oil?

From the different dissolved gas analysis methods, it was identified that the main value is the accuracy of the diagnosis and the second is the speed at which it can detect the abnormal condition.

The pure ratio-based methods like the Rogers and Doernenburg methods are not effective in identifying diagnosis for all samples recorded. This is due to the limits in the ratios which causes gaps where no diagnosis is possible.

The Duval's Triangle 1 gives good results in identifying faults in transmission transformers however it cannot provide a healthy diagnosis. From the case studies it is clear that the progression of the fault can be picked up with the LEDT, MEDT and Duval's Triangle 1 and Pentagon. Both the LEDT and MEDT provides a trend from normal state to abnormal state which is clearly visible using the R-Value trend.

It was identified from the cases studies that the Duval's triangle 1, Pentagon and LEDT with R-value offers good results in identifying the internal condition of transmission transformers.

Can more than one of the above methods be combined to predict the condition of the transformer accurately?

LEDT method can be combined with the Duval's Triangle 1 to give an appropriate prediction of the transformer condition. Based on the fact that LEDT can detect the incipient fault at the normal stage with the aid of its intelligence to use the low temperature and Duval's triangle 1 being capable of using high temperature dissolved gases, that combination can interpret the results successfully for the full range of faults. The R-value trend from the LEDT methods offers a major advantage in tracking the progression of faults over time from the normal to the abnormal regions.

To what extent can these methods developed for mineral oils be used to assess the condition of a transformer filled with ester oils?

The existing incipient fault identification methods such as ratio coding methods of Rogers and Doernenburg ratios on the previous study produced wrong interpretation for ester oil because the calculated values from the dissolved gas results from non-mineral oil does not fit on the coding scheme limit [Gomez 2014]. Therefore, ratio coding methods do not offer value in diagnosing incipient faults in ester oil filled transformers.

Based on the published papers, the Duval's Pentagons method 1 was not designed to detect the incipient fault and to diagnose faults in dissolved gases from the ester oils.

The LEDT method has the advantage to detect the incipient fault from oil and ester filled GSU and Tx transformers because of utilising low-temperature gases and it will indicate the fault while is in a normal stage but to diagnose the incipient fault will need the adjustment on the boundaries zone to give more accurate results.

Duval's Triangle 1 gives good results and identified very well the cause of fault gases formation in the ester oil. Duval's Triangle 1 has an advantage of DT zone which shows the transition of the fault to escalate to another fault zone.

Based on the outcome of the investigation done on this study, it was indicated that the coding ratio methods cannot be utilised to assess the condition of the transformers/ reactors filled with ester oils, because of the misinterpretation from the coding scheme.

The LEDT method has an advantage that can be used better to assess the transformer filled with ester oils because its intelligence can detect the incipient fault at the early stage that gives an engineer a chance to plane an outage in time and required maintenance. The only limitation is that high levels of carbon monoxide are produced in ester oils. The LEDT has been designed to limit the CO levels to 350 ppm which limits the issue of high CO levels.

7.3 Assessing the Hypothesis

The hypothesis tested in this study is can t*he LEDT method identify early detection of insulation degradation and incipient faults in transmission transformers for both mineral and ester oils.*

This study methodically investigated the various aspects of this hypothesis with first identifying the sources of low energy faults within the power transformer and then identifying the components that are most affected by this energy. The development and theory of the Low Energy Degradation Triangle model was investigated and tested previously on GSU transformers with positive results. Due to transmission transformers generally being lightly loaded when compared to fully loaded GSU transformers it was necessary to have this assessment as the degradation process may not be that significant in transmission transformers.

The research questions provided the necessary theory and methodology to test the hypothesis. In line with the development of the LEDT the combustible gases hydrogen, methane and carbon monoxide was deemed most effective in capturing the possible effects of low energy degradation even within the lightly loaded transmission transformers.

On this basis the LEDT was assessed in this study by application on seven case studies based on transmission transformers to take a retrospective approach in analysing its diagnostic capabilities. These case studies provided invaluable information by confirming transformers operating normally and changes to the abnormal state that have resulted in either a failure or removal of the transformer from service.

One of the distinct advantages of the LEDT was the ability in providing a visual trend of the deteriorating state of the transformer insulation which was confirmed with the visual inspections of transformers that were taken out of service. The defective state trigger was received well in advance of the final failure event on all the case studies investigated. The true defective state triggers were confirmed even when the dissolved gas samples were well within the normally accepted limits or fluctuated erratically.

The R-value trend also provided valuable time-based trend which clearly indicated when the transformer was moving out on the normal region into the fault regions. This was also effective in identify the progression of the fault until failure.

Majority of case studies presented started off with low dissolved gas levels even when the transformer was taken out of service and the oil processed which clearly put the samples into the normal region of the LEDT. Thereafter it was found that increases in the dissolved gases resulted in the movement to the abnormal state where failures occurred finally occurred. It was found that most of the evidence presented was as the result of hotspots in the tap changer connections and leads which was confirmed only after failure from internal inspections. It was also identified the fault progression on one of the transformers took a few years until final failure suggesting slow fault degradation of the insulation which was confirmed with a hotspot on the HV lead that was heavily insulated with paper insulation that absorbed most of the heat generated by the fault.

The assessment on non-mineral oils like natural and synthetic ester also provided useful results with regards to the LEDT identifying faults in these transformers. The study was based on published samples from simulated thermal and discharge experiments. These suggest that the LEDT can formulate a diagnosis on transformers filled with natural and synthetic esters. It is however clear that this must be further tested on real sample data from transformers in service with non-mineral oils.

From the literature research and analytical analysis of dissolved gas data of the seven case studies on the transmission transformers there was significant evidence to support the hypothesis that the LEDT can be a valuable tool in assessing the insulation degradation and incipient faults in transmission transformers. There is also evidence to suggest that the LEDT can offer positive results for transformers filled with natural and synthetic esters.

7.4 Conclusion

It was identified from the theory and detailed analysis of case studies on transmission transformers that the LEDT method offered significant advantage in identifying the condition of the power transformer based on the level of insulation degradation. In most instances the fault triggers a few years before final failure occurred. The most important aspect of the LEDT is the R-Value trend which provides a visual time-based trend of the progression of faults within the transformer.

The important aspect is that the LEDT method can be effectively used with other diagnostic methods like the Duval's' Triangle, Duval's Pentagon and MEDT method to provide an accurate assessment of the type of faults within a power transformer.

It is highlighted that with regards to natural and synthetic esters as an insulation medium the LEDT has currently only been tested on simulated data and must be applied on real samples taken from transformers filled with these oils.

The assessment on ester oil also provided a mean full result with regards to LEDT identifying faults in these transformers. The study was based on published samples from simulated thermal and discharge experiments.

7.5 Future work

The LEDT method has been proven to offered valuable diagnosis in GSU transformers and in this study of transmission transformers within the Eskom fleet of transformers. It is felt that the diagnosing accuracy can be improved with application on a wider database from international fleet of transformers covering different environmental and operating conditions. These suggest that the LEDT can formulate a diagnosis on transformers filled with natural and synthetic oil. It is, however, clear that this must be further tested on real sample data from transformers in service with non-mineral oils.

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