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INFLUENCE DE PRODUITS DU VIEILLISSEMENT SUR LES PROPRIÉTÉS PHYSICOCHIMIQUES ET LA TENDANCE AU GAZAGE DE FLUIDES ISOLANTS UTILISÉS DANS LES TRANSFORMATEURS DE PUISSANCE

par Luc Loiselle

Thèse présentée à l'Université du Québec à Chicoutimi comme exigence partielle du doctorat en ingénierie

Québec, Canada

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INFLUENCE OF AGEING BYPRODUCTS ON THE PSYSICOCHEMICAL PROPERTIES AND GASSING TENDANCY OF INSULATING FLUIDS USED IN POWER TRANSFORMERS

by Luc Loiselle

Thesis presented at the Université du Québec à Chicoutimi in partial fulfillment of requirements for the degree of doctor of philosophy in engineering

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RÉSUMÉ

Lors de la production, du transport et de la distribution électrique, l’énergie circule au travers d’infrastructures critiques. Parmi ces infrastructures, on note le transformateur de puissance qui est l’élément le plus onéreux du réseau et un des plus critiques. Tout au long de sa vie utile, le transformateur est soumis à différentes contraintes. En fonction de la sévérité et du temps d’exposition à ces dernières, cette durée de vie en sera affectée. Parmi ces contraintes, on distingue évidemment les contraintes électriques et thermiques. Ces contraintes produisent différents gaz qui sont déterminés par chromatographie gazeuse et analysés via ces gaz dissous différents outils.

Actuellement, les techniques modernes d’analyse des gaz dissous telles que le triangle de Duval, les ratios de Rogers, etc. ne tiennent pas compte de l’état en service de l’huile. Autrement dit, quel que soit l'état de dégradation de l'huile du transformateur, les mêmes outils de diagnostic sont utilisés.

L’objectif global de ce travail de recherche est d’améliorer notre compréhension sur l’influence des sous-produits du vieillissement sur la tendance au gazage et à la dégradation de liquides diélectriques de transformateurs. Plus spécifiquement, nous prévoyons étudier l’influence du vieillissement sur la dégradation et la tendance au gazage de différents fluides en simulant des défauts à faible énergie (décharges partielles), haute énergie et défauts thermiques. De plus, l’évolution des particules de dégradation solubles et colloïdales dans ces fluides a été étudiée.

Pour atteindre ces objectifs, une étude expérimentale a été conduite. Les différentes étapes consistent à :

- réaliser des vieillissements thermiques pour avoir des fluides avec un historique paramétré,

- reproduire les différentes contraintes,
- isoler les différents produits de dégradation et
- procéder aux analyses.

Les trois types de fluides étudiés sont l'huile minérale, l'ester synthétique et l'ester naturel.

- Résultats expérimentaux

Pour l'impact des décharges à basses énergies (décharges partielles), l'ester synthétique est le fluide le moins influencé au niveau du changement de la production des gaz, suivi l'huile minérale.

Pour l'impact des décharges à haute énergie, l'ester synthétique est le fluide le moins influencé au niveau du changement de la production des gaz, l'huile minérale est moins bonne.

En ce qui concerne l'impact des défauts thermiques, l'ester synthétique est le fluide le moins influencé au niveau du changement de la production des gaz, viennent ensuite l'ester naturel et l'huile minérale.

Concernant l'influence des produits colloïdaux et des particules dissoutes, il n'y a pas eu d'observation de particules de produits colloïdaux dans les esters. Les résultats démontrent aussi que les esters naturels génèrent une plus faible quantité de boue.

ABSTRACT

During the production, transmission and distribution of electricity, energy flows through critical infrastructure. Among these infrastructures, the power transformer is the most expensive element of the network and one of the most critical. Throughout its useful life, the transformer is subjected to various stresses. Depending on the severity and time of exposure to them, this shelf life will be affected. Among these constraints, there are obviously electrical and thermal constraints. These stresses produce different gases which are determined by gas chromatography and analyzed via these dissolved gases different tools.

Currently, modern dissolved gas analysis techniques such as Duval's triangle, Rogers ratios, etc. do not take into account the in-service condition of the oil. In other words, regardless of the state of degradation of the transformer oil, the same diagnostic tools are used.

The overall objective of this research is to improve our understanding of the influence of aging byproducts on the gassing and the degradation tendency of dielectric transformer liquids. More specifically, it is planned to study the influence of aging on the degradation and the gassing tendency of different fluids by simulating low energy (partial discharges), high energy and thermal faults. In addition, the evolution of soluble and colloidal degradation particles in these fluids was studied.

To achieve these objectives, an experimental study was conducted. The different stages consist of:

- performing thermal aging to have fluids with a configured history,
- reproducing the different stresses,
- isolating the various degradation products and
- carrying out analyzes.

The three types of fluids studied are mineral oil, the synthetic ester and the natural ester.

- Experimental results

For the impact of low energy discharges (partial discharges), the synthetic ester is the fluid least influenced by the change in gas production, followed by mineral oil.

For the impact of high energy discharges, the synthetic ester is the least influenced fluid in the change in gas production, mineral oil is worse.

Regarding the impact of thermal stress, synthetic ester is the fluid least influenced in changing gas production, followed by natural ester and mineral oil.

Regarding the influence of colloidal products and dissolved particles, there was no observation of particles of colloidal products in esters. The results also show that natural esters generate a lower amount of sludge.

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LISTE OF ABREVIATIONS

BHA : Butyalted Hydroxy Anisole

BHT : Butylated Hydroxy Toluene

BDV : High energy discharge

BOD : Biological Oxygen Demand

°C : degree Celcius

cSt : Centistokes

DGA : Dissolved Gas Analysis

DBP : 2,6-ditertiary-butyl phenol

DBPC : 2,6-ditertiary-butyl paracresol

FR3 : Natural ester made by Cargill

GA : Gallic Acid

HS : Thermal stress (hot spot)

IEC : International Electrotechnical Commission

IEEE : Institute of Electrical and Electronics Engineers

Kg/m^3 : kilogram / cubic meter

kV : kilovolt

kVA : kilovolt amperes

KOH : Potassium hydroxide

mN/M : millinewton / meter

MO : Mineral Oil

NE : Natural Ester

NTU : Nephelometric Turbidity Units

OHS : Occupational health and safety

PCB : Polychlorinated biphenyl also call askarel

PD(s) : Partial Discharge, low energy discharge or stability test.

PFAE : Palm Fatty Acid Ester

PMMA : Poly(methyl Methacryalate)

REC : Reclaimed

SE : Synthetic Ester

UV/vis : Ultraviolet – visible spectroscopy

W/mK : Watt / meter per Kelvin

µl/min : microliter per minute

Ω-m : Ohm meter

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Pour toi maman

CHAPTER I

GENERAL INTRODUCTION

1.1 INTRODUCTION

Actually, power demand has been constantly increasing with population as it relies on electrical energy for simple things like lighting, heating and cooling of homes, power televisions and computers. The next big increase for the next years is the deployment of electric cars. Just as an example, the last release of the Québec's electrical code implement mandatory the requirements for the provision of room in the electrical panel for electric vehicle charging infrastructure in certain new construction [1]. It will have definitely changed the consumption on the grid as the affordability of electric cars is getting better and the range has consistently increased [2]. In the United States, where transportation accounts for 29 percent of total energy use per year, the country is witnessing a slow but steady shift from gasoline and diesel fuel to electricity—with electric vehicles (EVs). EVs are now forecast to represent 11 percent of all passenger vehicle sales by 2025, and 55 percent by 2040 [3]. Obviously, it requires a strong and reliable grid to be able to carry this power from the powerhouses to the loads. To make the grid reliable, appropriate tools are required for suitable maintenance and incipient failure prediction. Recall that the most critical part of the grid is the power transformer. It is then really important to determine with the appropriate analysis, the optimum moment of a transformer's replacement or repair. The appropriate detection of faults is then a key factor. As the age of the transformer's units are increasing year after year, it requires a good way to determine in priority the units to change and to maintain appropriately the grid.

1.2 MOTIVATION AND RESEARCH OBJECTIVES

Nowadays, the condition of in-service aged oil is not considered in the analyses of dissolved gas in power transformers. Aging of oil can be measured by interfacial tension (IFT) or acidity (NN). The hypothesis is that the type and the amount of gas would be affected by the acidity. The objective of this research is to demonstrate that the quantity and type of gas generated from the oil in the transformer is affected with time in service. If this proof of concept is proven to be true, it will lead in the future to the improvement of the diagnostic tools. As far as we know, no diagnostic method exists taking into consideration the acidity or state of the oil for measuring gassing [4].

1.2.1 General Motivation

From a statistical point of view, the transformers in service worldwide are getting older as years are passing by. Some of them are replaced or refurbished when problems are suspected or detected. Age statistics [5, 6] show that many 50-year-old or older transformers are still in service. It is important to maintain the transformer fleet in good working service as their replacement may be very expensive. So, appropriate diagnostics are mandatory to plan the optimum time for their replacement or repair. This approach is not only an economic gain, but also an environmental gain as fewer resources are used for the replacement of the transformers.

Power transformers are the most expensive equipment on the grid and can represent up to 60% of the investment of any power substation [7]. Investment in transformers worldwide represents hundreds of billions of dollars.

The cost of changing transformers is expensive as it may take up to two years to manufacture a transformer and put it into service [6]. The goal is to predict as accurately as possible incipient failure using predictive tools. The idea is to improve the time the transformers are in service and predict the replacement of the units before the breakdown happens.

On July 6, 2010, at the Rio Tinto Alcan Laterrière plant, two transformers ignited [8]. These two ignitions disabled half of the electrolysis pot rooms of the plant. The operation and maintenance team were able to restart the electrolysis rooms, only two months after the event, at a cost of more than fifty (50) million dollars just to jack drill the pots and restart the pot room where liquid aluminum froze while there was no electricity feeding the DC busbar. Luckily, there were no oil leaks in the environment in this particular case [8]. The transformers were recovered, repaired and restarted. Fortunately, the cost of these two transformers and the delay to get new units would have been staggering in the event of a replacement.

On December 11, 2010, at the Chute-des-Passes power plant of Rio Tinto Alcan, a transformer ignited (Figure I-1) [9].

Figure I-1: Chute-des-passes breakdown.

This resulting oil leakage has an important cost. Important fines were imposed excluding decontamination costs, given the remote location and the revenue lost in production loss.

If oil spills or is disposed of in water bodies, the composition of mineral oils affects the environment more permanently than biodegradable liquids. It can cost a lot of money to process to decontamination depending on where the leaks happened. It costs money to proceed to the decontamination and companies can get fined as well. In Québec, it might cost up to $6,000,000 in fines and up to three years of imprisonment [10]. High operational temperatures in transformers may lead to fires, explosions creating an element of risk for the operating personnel. Employers who exercise due diligence take all reasonable precautions in the circumstances to prevent accidents and protect the health and safety of workers [11].

1.2.2 Scientific Motivation and Research Objectives

In recent years, many researchers have been developing improved tools to perform the diagnosis of in-service transformers. However, few researchers dedicated their works on the root cause of gassing.

The production of gases is affected by different factors. With these factors, the actual condition of the oil (that can be measured by acidity and interfacial tension) is influencing the volume of gases produced. Unfortunately, there is no tools or method that takes into account the aging of the oil on the diagnosis of the gassing of in-service transformers.

The global objective of this work is to understand the influence of aging byproducts on the tendency of gassing and liquid degradation. Emphasis has been laid on electrical and thermal faults on the liquid degradation and the gassing tendency at different aging conditions (based on acidity values). In the present thesis, the influence of electrical and thermal fault of mineral oil, synthetic esters and natural esters on the degradation and the gassing tendency at different aging conditions has been reported.

The colloidal particles and dissolved particles are the oil samples aging indicators. There is no quantification or comparison on the colloidal particles and dissolved particles in the aging process for the different fluids. The degradation products are a combination of soluble and colloidal particles. Hence efforts are made to understand the individual influence. A centrifuge apparatus and laboratory made setup (provided with fuller’s earth) have been used to separate colloidal and dissolved particles respectively.

Therefore, the following specific objectives listed below have been the focus of the present research. These specific objectives are defined according of the existing literature and challenges of using ester dielectric fluids for transformer insulation technology.

- The 1st specific objective is to investigate the influence of thermal aging on oil degradation and the gassing tendency for mineral oil and synthetic ester under low energy discharge electrical faults;
- The 2nd specific objective is to investigate the influence of thermal aging on oil degradation and gassing tendency under high energy electrical discharge faults for mineral oil and synthetic ester;
- The 3rd specific objective is to investigate the gassing tendency of fresh and aged mineral oil, synthetic ester and natural ester under electrical and thermal fault conditions and the impact of faults on the liquid degradation;
- The 4th specific objective is to understand and investigate the monitoring of soluble and colloidal decay particles in mineral oil and ester liquids.

1.3 ORIGINALITY OF THE PROJECT

The actual age of transformers in service, together with the ever-increasing demand for energy, definitively increase the potential risk of unanticipated breakdowns, with consequent very high monetary losses. Replacing these equipments with new ones - only because of its age - is clearly out of reach for any company. Some transformers in service may thus fail, leading to significant cost implications for the operator and, in extreme cases, to an explosion with possible serious damage and even death of workers, including significant impact on the environment. The goal and best course is to diagnose the behaviour of the transformers to prevent breakdowns using diagnosis and prognosis testing of the liquids. The most common test performed for transformers in service is Dissolved Gas Analysis (DGA). DGA interpretation techniques have been used for a long time and providing information to diagnose the units in service [12]. Unfortunately, these techniques do not take into consideration the aging of the fluid and it is believed that this can lead to misinterpretation of the results. So, the first hypothesis is that a fresh fluid (out of the barrel) won’t develop the same gassing trend or tendency as an aged one. The tests performed in this research are aimed to understand the influence of the liquid degradation (aging byproducts) on gassing tendencies. In addition, various operational faults also influence degradation and gassing tendency as well. More precisely, the first hypothesis is aimed at finding gassing tendencies of insulation liquids under different faults at different states (aging) of the liquid.

The second hypothesis, a logical continuation of the first one, is that ester can dissolve more sludge than mineral oil. This hypothesis goes along with the theory that for the same acidity level, ester is less affected by the same level of the different stress than mineral oil.

The last hypothesis, to terminate the logical sequence is that the soluble decay content is involved with the deterioration of ester fluid.

Faced with the ever-increasing demand for energy, managing the overload of power transformers has become a very important issue for electricity companies across the globe. This research project makes it possible to highlight the role played by the quality of insulating oil on transformer degradation in general.

1.4 THESIS ORGANIZATION

The framework of the present research is focused on achieving the above objectives. It should be mentioned that the global objective is to understand the influence of aging byproducts on gassing tendency and liquid degradation. Following this line, the four specific objectives of this research have been reached by publishing four articles in renowned journals in the field of high voltage electrical. To discuss the present research and attainment of the objectives in an effective manner, this thesis is organized as follows.

Chapter 1 presents the introduction, the motivation and the research objectives, as well as the originality of the project, the thesis organization and the sources.

In Chapter 2 is found the literature review comprising the background of oil filled transformers, classification of transformer oils, dissolved gas analysis and common techniques used for diagnosis analyses. The current state of the art concerning alternative liquid dielectric fluids is central to this review.

Chapter 3 presents the first objective of the research, namely low energy (partial discharge) electrical faults, in the form of ***Publication 1: Published in MDPI Energies***: *Influence of aging on oil degradation and gassing tendency for mineral oil and synthetic ester under low energy discharge electrical faults.*

Chapter 4 presents the second objective of the research, namely high energy (arcing) electrical faults, in the form of ***Publication 2: Published in IET High Voltage****: Influence of aging on oil degradation and gassing tendency under high energy electrical discharge faults for mineral oil and synthetic ester.*

Chapter 5 presents the third objective of the research, namely thermal faults, in the form of ***Publication 3: Published in MDPI Energies***: *Gassing tendency of fresh and aged mineral oil, synthetic ester and natural ester under electrical and thermal fault conditions and the impact of faults on the liquid degradation.*

Chapter 6 presents the fourth objective of the research, namely the influence of colloidal and soluble particles, in the form of ***Publication 4: Published in IEEE Transactions on Dielectrics and Electrical Insulation***: *Monitoring Colloidal and Dissolved Decay Particles in Ester Dielectric Fluids.*

In Chapter 7, the findings and contributions of the research are summarized, including limitations of the research and its future development.

1.5 CREDITS

The central part of this work consists of four chapters that were written in the form of journal papers to allow publication of the results and ideas presented in this thesis. The four papers were published in the following journals: Multidisciplinary Digital Publishing Institute (MDPI) Energies, The Institution of Engineering and Technology (IET) and Transactions on Dielectrics and Electrical Insulation (TDEI) of the Institute of Electrical and Electronics Engineers (IEEE). The manuscripts have been written by the author, and the ideas presented therein are his own. In so doing, he was guided and helped by Pr. Issouf Fofana and Dr. U. Mohan Rao, who acted as supervisor and co-supervisor of the thesis. Both especially helped the author in the research design, timely review of the manuscripts, and the improvements.

CHAPTER II

LITERATURE REVIEW

2.1 BACKGROUND ON OIL FILLED TRANSFORMER

Power transformers are among the most important units on the power grid, in production, transport, and distribution. They are also used in special applications such as rectifiers in the electrolysis process. They are crucial components because they allow the voltage to be transformed to desired values. As an example, step-up transformers can reduce the current on transmission lines by increasing the voltage and thereby reducing losses and the size of the conductors. From a technical point of view, it would be unthinkable to transport the energy on long distances without transformers.

The average age of large power transformers in service in the United States is approximately 45 years, with 70% of them being 30 years or older [13]. Industry and cities require more and more electrical energy as demand is increasing, population is growing and acquisitions of the electrical cars are booming, leading to acquisition of electrical equipment, including power transformers of increasingly huge capacity. The presence of a large quantity of older equipment combined with the addition of new transformers often undersized or at the limit of required power is not helping the grid on the long term. It is also good to mention the loss of expertise of companies following the massive retirement of experts and budget reductions on maintenance and on investments increase the risk of a breakdown of transformers. In this situation, the likelihood of a breakdown increases daily with high monetary losses.

The replacement of exhausted transformers is a cost that most companies cannot afford, as they account for almost 60% of the total investment cost of a substation [7]. Only for the purchase of all transformers worldwide, investments would be up to hundreds of billions of dollars. The cost of the installation, maintenance, shut down and production losses are expensive as well. It is essential to mention that the consequences for hospitals and critical assets like water supply are not quantifiable. On the other hand, securing the assets by finding a more reliable way to diagnose the transformers would be a smart strategy.

Traditionally, the insulation and cooling systems of transformers have been done using mineral oil extracted from crude oil. Crude oil is not renewable and will eventually vanish. As mineral oil is not produced from a renewable source, it is not possible to rely on for the long term.

Spite the fact that the dielectric properties of mineral oils are widely accepted, the challenge remains that the transformer demand for high insulation levels requires exceptional dielectric performance, in particular for resistance to dielectric breakdown. For example, there are mineral oils which have breakdown voltage values of 50 kV in new condition according to ASTM D877 or D1816. There is an interest in increasing breakdown voltages. Significant internal heat is generated by different phenomena like the core and coil losses in operating transformers. It is problematic for an insulating medium to provide effective insulation and capacity to deal with higher temperatures. In the event of arcs or short circuits, the dielectric fluid must withstand a high temperature rise. This results in higher property requirements such as the flash and fire points in insulating fluids. The challenge is interesting as it is important to keep properties at appropriate levels, like keeping the pour point as low as -50 °C for northern countries.

Typically, mineral oil flash point should be in the range of 180 °C to 220 °C, according to the manufacturers [14].

Transformer insulation system is not designed to interact with moisture and environmental air, but contamination is unavoidable in most cases. Moisture, which is considered an enemy number one of insulation, can be at the origin of catastrophic failures since breakdown strength decreases as moisture content increases [15]. Oxygen act as ageing catalysts while heat, ageing byproducts, dirt, vibration, electrical stress, etc. will accelerate the degradation process [15]. If the breakdown voltage decreases too much, it may create a breakdown inside the power transformer.

Moisture can be evolved by cellulose insulation paper and by leaks from sealed transformers. Moisture is generated during the decomposition reaction of cellulose chains as well and enter from the external environment through the breather when silica gel is exhausted for non-sealed units. Moisture can also come from contaminated new or used oil barrels [16]. In this situation, the fluid undergoes oxidative degradation in the presence of oxygen to give a number of oxidation products. Acidic materials are the final products of oxidation affecting the characteristics of the insulating fluid as well as causing damages to the components of the electrical unit eventually sludging and clogging the paper.

Oxygen is a diradical species and the reactions of the oxidative process are complex, also involving free radical reactions. Adding oxidation inhibitors is a way to prevent these types of reaction, terminating the free radical process of oxidation [17]. The two most commonly used inhibitors for mineral oil are 2,6-ditertiary-butyl phenol (DBP) and 2,6-ditertiary-butyl paracresol (DBPC).

As soon as the cap is removed from the oil barrel, oxidation begins. When the transformer is energized for the first time on commissioning, oil gassing also begins. Even though these primary decay products are short-lived free radicals, as long as normal hydrocarbon chains surround and trap them, almost all pairs recombine and no net chemical reactions can take place. This phenomenon, known as the “cage effect”, occurs when the population of free radicals is minimal and the thermal agitation of molecules is low. However, as the free radical concentration increases, random chemical reactions between free radicals occur and soluble and insoluble oil-born decay products are produced. J. Tanaka at the Nineteen Symposium on Electrical Insulation underscored the paramount importance of free radicals in the physical organic chemistry of mineral oils [18].

Some utilities have already started replacing mineral oil with degradable fluids in their distribution transformers. The new insulating fluids need to have a number of specific properties and be compatible with other transformer materials. Some of the biggest advantages of using natural fluids over mineral oils are their biodegradability, high flammable limit, and longevity [19].

2.1.1 AGING

It is customary to oversize transformer insulation systems (which is the Achilles heel) to make sure of its dielectric strength under operating voltage [20]. However, the application of the operating voltage combined with electrical, mechanical, thermal and environmental stresses, and their mutual interactions, is causing gradual deterioration and aging of the insulators (Figure II-1) [21]. This degradation, mainly accelerated by the electric field, temperature, oxygen and humidity increases the risk of failure, leading to significant financial implications in terms of operating losses, repairs or replacement costs and, in extreme cases, explosions with possible irreversible damage or human death, in addition to significant environmental effects [8, 22, 23].

External faults occur on the devices in direct connection with the transformer. Generally, protections are installed for protection against damage to the transformer. Among these external faults, it is possible to cite [24] :

1. Overvoltage and over excitations caused by operations on lines, generators and loads;
2. Short circuits on lines or between lines and ground;
3. Transient overvoltage created by atmospheric conditions;
4. Faults in the external cooling system.

Internal faults are observed on the transformer components, which for the most part require a specific analysis in order to be detected. As examples of internal faults, these can be mentioned: magnetic core, core clamp, windings, connections, paper, oil, and tap changers.

A hotspot is a heating abnormality observed on active devices located at specific place(s) in the transformer.

- **Overheating** results from an abnormal overloading that generates heat inside the transformer;
- **Internal short circuits** between windings or between windings and the magnetic core or tank. Faults to ground can be added to this category. Short circuits will generate a different amount of energy depending on various factors such the inside faults, duration, current available from the grid, etc;

- **Oil leaks**: A transformer has many rubber seals, typically at the bottom of the tank, at the base of the terminals, and at refrigeration connections. Over time, these joints can degrade, harden, and cause leaks;
- **Degradation of the insulation** happens in operation as transformer insulation is subject to electrical, thermal, mechanical and environmental constraints. Paper and oil interact to produce extractable compounds that are used in fault diagnosis;
- **Oil oxidation** is influenced by heat, oxygen and facilitated by the presence of metal;
- **Hydrolytic reactions** happen in the presence of water and acid in the oil.

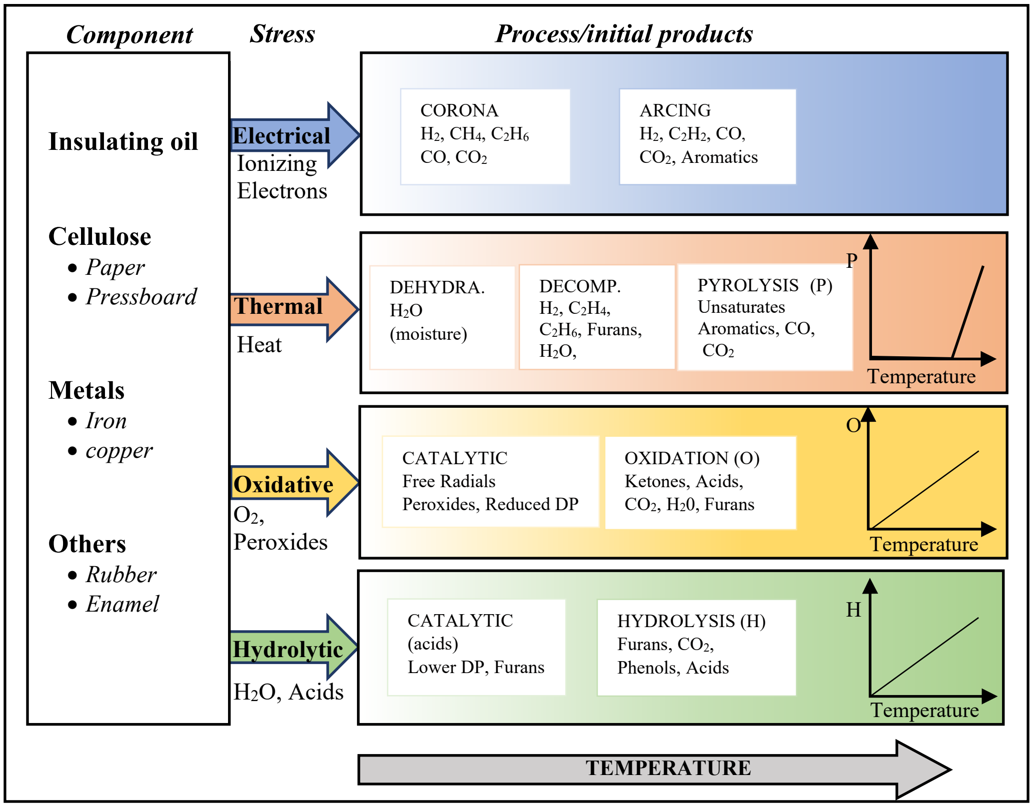

Figure II-1: Simplified mechanism of decomposition in transformer insulation [25].

For electrical stress, oil deteriorates and generates free radicals while witnessing decompositions of solid insulation. This will also introduce gassing in oil and partial discharges across the insulation. For thermal stress, oil is oxidized and oil sludging is initiated while the tensile strength of paper is reduced by cellulose fiber deterioration. This also creates scope for acids, water content, and dissolved gases. For oxidative stress, oxidation involves the production of acids and water in the oil. This water expedites hydrolysis and hampers the polymerization of cellulose paper [26]. The severity of oxidation and hydrolysis in mineral oils tends to increase sludging and induce catastrophic failure and premature aging of the transformer if the oil is not properly maintained by reclaiming, degassing and dehydrating when required. For hydrolytic stress, the rate of hydrolysis is higher in mineral oil than in ester fluids, leading to the production of acids, furanic compounds and carbon dioxide in the oil. Similarly, oxygen ingress works with gases liberated from insulation paper due to temperature; it also expedites oxidation.

2.1.2 TRANSFORMER FAILURES AND THEIR CAUSES

Transformer failure can be considered as an unwanted event causing the breakdown of service of one or more transformer functions. It signals the end of the capacity of a transformer to perform its specified function. In studying the reliability of transformers, it is often difficult to distinguish between major and minor failures. Consequently, the following terms are proposed: failure with forced stop, failure with programmed stop and faults. A failure with a forced stop is a failure that stops the operating conditions of the equipment and it is not planned. A failure with a programmed stop is based on indicators that provide the information of the abnormal conditions and the stop is planned according to the failure. A fault is an abnormal condition which can damage the electrical equipment and disturb its normal conditions. It is useful to recall the definitions of the terms used, when talking about failures on a power transformer, as specified in the IEEE C57.125-2015 Standard [27].

2.1.3 CONDITION ASSESSMENT OF THE TRANSFORMERS

The assessment of the condition of a transformer is an activity that is integrated into the maintenance of a transformer, so that it permanently assumes its role in the availability of electricity supply. It is a question of ensuring, at a given time, the conditions of use of the transformer, to identify any risk of unwanted events or simply failure. A set of measures is made either in the case of a maintenance policy, or in the case of a specific alert. In general, the condition of a transformer can be accessed from information on:

- The health status of the oil;
- The state of health of the paper;
- The state of health of the internal parts;
- The age of the transformer.

If maintenance is neglected and sludge is found to be present in the oil, it is a visible indication that oil needs to be regenerated or disposed. The solid insulation (paper and pressboard) can be clogged by the sludge and create cooling problems [15]. Any failure or unexpected degradation of the oil-paper insulation is accompanied by a change in the colour of the oil. Assessment of oil colour, and oil status as well as corresponding recommendations are summarized in Table II-1.

Table II-1: Oil colour changes as related to degradation [28]

Transformer oil colour						
Fresh	Acceptable	Marginal	Questionable	Critical	Poor	Unacceptable
State of the oil						
Fresh and unused	The parameters of oil in service are within acceptable limits.	Polar solvents and oxidation byproducts are developed. Oil interfacial tension is decreasing.	Dissolved gases and small amounts of soluble products are produced.	Soluble sludge is initiated. The acidity of the oil increases. The corrosive concentration of sulphur and furan increases.	Sedimentation suspended solid particles and viscosity increase.	Highly aged oil and parameters beyond critical limits.
Effects on the transformer						
Suitable as heat transfer fluid and dielectric fluid.	Can continue to be used as coolant and dielectric.	When interfacial tension decreases, electrical rigidity of the oil decreases, which indicates presence of water.	Important stage of the beginning of premature aging of paper-oil complex and emerging faults initiated.	Deposition of sludge on core and windings. Damage to internal parts.	Fins and cooling tubes will be blocked. Increase in transformer temperature.	No longer able to effectively serve as insulation or coolant.
Recommendations						
None	None	Add antioxidant	Dehydration and degassing of the oil or reducing load applied to the transformer.	Fuller's earth reclamation	Internal cleaning and reclamation of oil from Fuller's earth.	Stop the transformer as quickly as possible. Internal cleaning and reclamation of oil from Fuller's earth.

Oil degradation can be measured with different values such as acidity (NN), interfacial tension (IFT), colour. The classifications are determined in Table II-2.

Table II-2: Transformer oil classifications [29]

	Good Oils	Prop A Oils	Marginal Oils	Bad Oils	Very Bad Oils	Extremly Bad Oils	Oils in Disastrous Condition
NN	0.00-0.10	0.05-0.10	0.11-0.15	0.16-0.40	0.41-0.65	0.66-1.50	≥1.51
IFT	30.0-45.0	27.1-29.9	24.0-27.0	18.0-23.9	14.0-17.9	9.0-13.9	-
Colour	Pale Yellow	Yellow	Bright Yellow	Amber	Brown	Dark Brown	Black

2.2 HISTORY OF TRANSFORMER INSULATING OILS

Various kinds of insulating fluids have been developed and then used to respond to the needs of the industry and environmental regulations. Figure II-2 summarizes the use of the different oils from the beginning to present time.

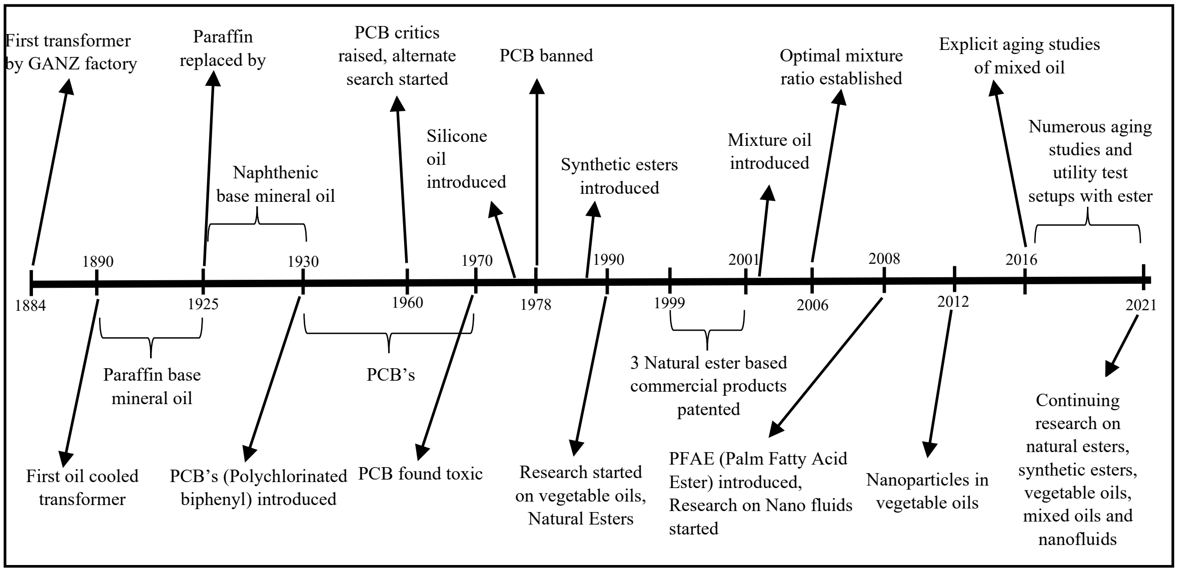

Figure II-2: Timeline development of transformer insulating fluids [30].

Mineral oil is still in use today as the main type of oil. The industry is changing slowly because the new types of fluids are not very well known by the operators of the equipment. It is important to mention that the industry is very conservative as bringing a new type of fluid can be complicated as nobody wants to be responsible for bench tests and possible consequences.

Liquid dielectrics made from petroleum-based oils have been used for transformers before 1887 [31]. As an example, in 1886 the Westinghouse Electric Company inserted stacked iron laminations into pre-wound coils, provisions for cooling and insulating transformers by oil immersion, and packaging assembly in hermetically sealed containers [32].

The first transformers have been using paraffin-based oil until around 1925 which was then replaced by naphthenic-based oil.

In 1892, a chemically stable mineral oil for use in transformers from petroleum was patented by Thompson which was then adopted a decade later by General Electric [33].

The first transformer using askarel was made in 1932 and it contained aroclor (polychlorinated biphenyl, PCBs). The use of aroclors as non-flammable insulating liquids continued until the mid-1970s when environmental issues were raised and it was later banned. PCB's were used in large scale as their fire resistance and dielectric were far better than mineral oil.

It took up to the 1940s to make mineral oil widely used in various high-voltage equipment such as transformers, capacitors, cables, and bushings [34].

At the same time in the 1970s silicon oils were introduced to replace PCBs as the former were nontoxic and had better properties. Silicone oils have excellent electrical insulating properties, higher fire points than mineral oils, admirable anti-oxidative properties and thermal stability due to their higher bonding energy of the (Si-O) siloxane bond. It is the justification why the silicone oils were able to replace PCBs.

In 1984, McShane et al. developed a synthetic ester with a high fire point suitable to replace askarels (PCBs). The specific design was developed for applications such as compact railroad traction and particle power supplies [35].

In the 1990s, synthetic esters were introduced as high dielectric strength, biodegradable, low viscosity and high fire point. Simultaneously, natural ester was under investigation as green technologies were pushed [36].

In 1993 for natural ester, twenty-four food grade base liquids and different blends were assessed. Some liquids contained a high percentage of unsaturated fatty acids, resulting in lower viscosity and better low-temperature properties. Others had a higher percent of saturated fats, which improved oxidation stability. The ratio between the two types of fatty acid oils required a careful balance [35].

In 1999 and 2001, three commercial products were patented for use in transformers based on different vegetable liquids (sunflower liquid, canola liquid, soybean liquid) [37-39]. Initially for the first natural esters, it was reported that oxidation stability was poor, and their application was at the first time restricted to sealed transformers. In 2002, efforts were made to improve the oxidation stability of new liquids by using suitable nanoparticles [40]. Investigations of the characteristics and performance of blended insulating fluids were reported in [41, 42]. In 2006, it was confirmed that a mixture of 80% mineral oil and 20% synthetic esters was a good compromise in order to improve the operating performance of insulating systems [43]. In 2018, palm fatty acid ester (PFAE) fluids were proposed because of their acceptable viscosity and high relative permittivity [44]. Also, several agricultural liquids were investigated worldwide to study their feasibility for applications in transformers. It was recently reported that a 80:20 mixture ratio of mineral oil and synthetic esters was optimized for applications in transformers [14, 45].

In 2019, a new type of vegetable liquid, Persea Americana liquid for transformers was proposed as a dielectric from researchers in Nigeria. Two types of samples were investigated included both food grade extra virgin Persea Americana ester (EVPAO) and refined Persea Americana ester (RPAO) [46, 47].

2.3 CLASSIFICATION OF TRANSFORMER FLUIDS

Though many different liquids are still available in the market at various times, many of them were withdrawn for various reasons. Today there are four generally accepted liquids, namely: mineral oil, silicone, synthetic ester and natural ester.

2.3.1 MINERAL OILS

Mineral insulating oils are hydrocarbons derived from crude petroleum. They have been used as dielectric fluid for several generations of transformers. It has a long-standing record of good performance and low costs. It is considered a top choice for transformers for outdoor installations. It has a very good dielectric and thermal performance. In fact, most of the standards for liquid filled transformers have been based on mineral oil. It is the largely preferred insulating liquids because of its long live in the market and the conservative mentality of the engineers involved in the high-voltage apparatus field. However, mineral oil is considered to be a flammable liquid and therefore, suffers from certain restrictions on its use and containment [48].

Mineral oils have been used as insulation in electrical equipment for more than a century. Depending on the origin of the oil and the refining process, different types of oils can be identified. Figure II-3 shows the refining process for crude oil. The refining process consists in extracting from the oil all the impurities in order to give it better properties. Depending on the type of process (hydrocracking, extraction or hydrogenation), oils of paraffinic, aromatic or naphthenic type are obtained.

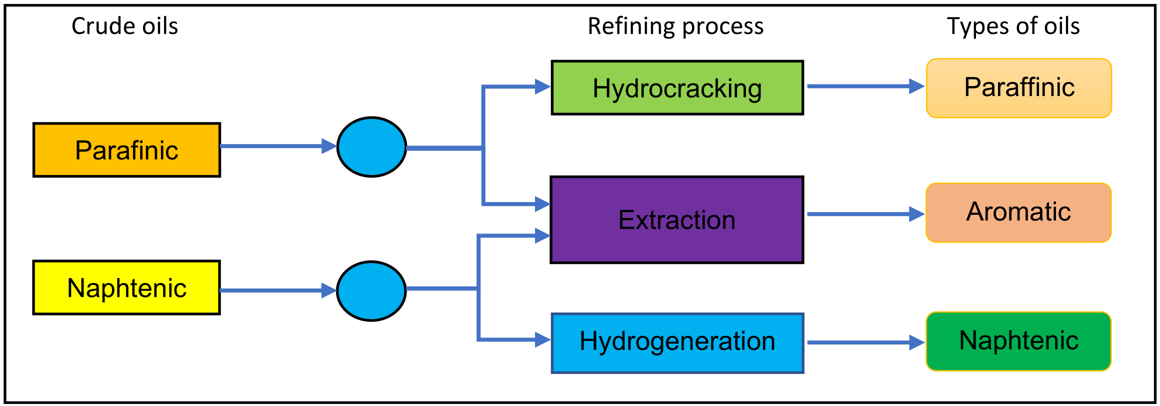

Figure II-3: Process of mineral oil refining [49].

Once the impurities have been removed, these oils become very complex mixtures; they can contain more than 3000 different hydrocarbons [50]. These molecules contain only carbon and hydrogen. A form of classification (as a percentage of the type of hydrocarbon) consists in classifying these mineral oils according to the content of paraffinic carbon (Cp), naphthenic carbon (Cn) and aromatic carbon (Ca). The two main types of mineral oil in use for transformers, produced from different oil refining processes are:

- **Paraffinic oil** which is refined and processed from crude oil. It contains significant quantities of naturally occurring n-paraffins. Additives may be required to lower the pour point as it is high.
- **Naphthenic oil** which is refined and processed from crude oil. It contains a very low level (or none) of naturally occurring n-paraffins. Naphthenic oil does not require additives to reduce the pour point as it is low. Naphthenic oil provides longer life expectancy and better viscosity characteristics than paraffinic oil.

2.3.2 SILICONE OIL

As PCBs were classified carcinogenic and persistent organic pollutants, a safer replacement liquid was quickly needed. So, enters silicone oil in the 70’s also known chemically as poly-dimethyl siloxanes or PDMS, which seemed to offer a solution. Although not biodegradable, the fluid was non-flammable, it was well priced, and it became widely used. It has a relatively high fire point and is generally self-extinguishing when the source of ignition is removed. Silicone has been used for many years in indoor applications, generally in vaulted areas. Silicone fluid is composed of halogen-free synthetic compounds that are products of polymerization. At high temperature, however, silicone can produce some chemicals which can be a health hazard. It has proven popular in retrofilling transformers. But times have changed, and the usage of silicone has declined. Better performing and environmentally superior alternatives such as ester fluids have come to market. For several decades, this was the preferred fluid when a “less flammable” liquid was required. Now, with silicone oil prices increasing a lot over the past years, it is the most expensive insulating fluid even if its economic attractiveness has soared. One of the biggest problems resides in the fact that it cannot be mixed with another fluid as it is not compatible. If it is mixed, it will produce a foaming interface and will create problems. So, for a retro fill it is complicated.

2.3.3 ESTER LIQUIDS

An ester is an organic compound where the hydrogen in the compound's carboxyl group is replaced with a hydrocarbon group. Esters are derived from carboxylic acids and (usually) alcohol. While carboxylic acid has the -COOH group, the hydrogen is replaced by a hydrocarbon in an ester. The chemical formula of an ester takes the form RCO_2R', where R is the hydrocarbon parts of the carboxylic acid, and R′ is the alcohol.

The term ‘ester’ comes from the chemical linkage, which is formed from the reaction of an alcohol and a fatty acid. Figure II-4 shows an ester linkage.

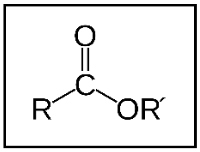

Figure II-4: The ester linkage.

As the name implies, the ester linkage occurs in both natural and synthetic esters but does not occur in mineral or silicone oils.

2.3.4 SYNTHETIC ESTERS

Synthetic esters are chemically formed substitutes for hydrocarbons. Synthetic esters are manufactured by combining alcohols and carboxylic acids in an esterification reaction. There are dozens of commercially available alcohols and acids to choose from, and many feedstocks are derived from vegetable or animal sources. Ester chemistry allows the user to formulate lubricant base stocks to meet virtually any lubrication challenge. Although not quite natural, synthetic esters still retain the favourable health and environmental benefits of the natural fluids.

Ester fluids for transformers are known as pentaerythritol ester or organic esters (as opposed to natural esters). They were developed following the banishment of PCBs for the impregnation of fire-resistant transformers. These esters are also known as tetra esters because they are obtained from a tetra alcohol (pentaerythritol) and a mixture of monocarboxylic acids containing from 7 to 9 carbons. The esterification is carried out at a 100 deg-C and is followed by neutralization, distillation and treatment on active earth [51].

A chemical reaction between polyol (molecules with more than one alcohol group) and synthetic or natural carboxyl acids yields synthetic esters whose molecular structure have multiple saturated fatty acid groups (mostly 2, 3 and 4) connected to the polyol backbone. There are seven main types of synthetic esters, namely diester, phthalate, trimellitate, pyromellitate, dimer acid ester, polyols, and polyoleates [52]. Pentaerythritol ester is an example of a commercially available synthetic ester insulating fluid from the polyols type which is produced from a branched mono-acid containing 5 to 18 carbon atoms and alcohol pentaerythritol [52, 53]. The molecular structure of Pentaerythritol synthetic ester which has four fatty acid groups connected to a central polyol backbone. The block diagram of the process of producing a synthetic ester is shown in Figure II-5. Since synthetic ester insulating fluid molecules only contain saturated fatty acids, it possesses excellent oxidation stability compared to both mineral oil and natural ester. Detailed technical specifications of new synthetic ester insulating fluids are available in IEC 61099 [54] and an in-service maintenance guide that is published as in IEC 61203 [55].

Synthetic ester insulating liquid: An insulating liquid that is a reaction product from the combination of an organic acid and an alcohol such as pentaerythritol [56].

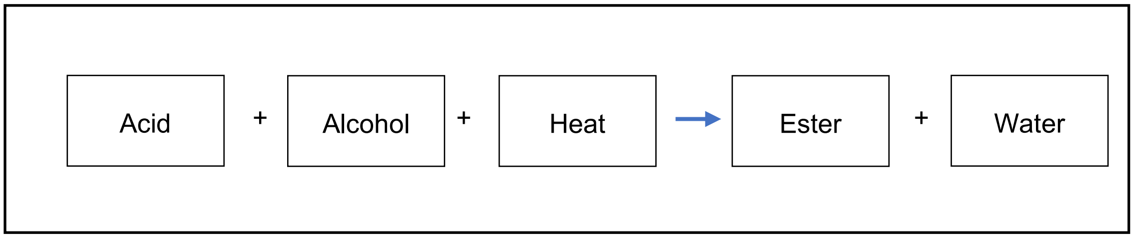

Figure II-5: Block diagram of the process of manufacturing a synthetic ester.

2.3.5 NATURAL ESTERS

Natural esters are made from renewable natural sources such as soybean, rapeseed, canola, etc., which are fatty acids generated in seeds and flowers which meet the requirements of “less-flammable” liquid. It is biodegradable and is environment-friendly. Natural ester can extend the insulation life by drawing out moisture from paper insulation. The heat transfer properties are inferior to that of mineral oil and transformers have to be suitably designed for that adding to the cost of the project. Also, certain precautions are needed during manufacturing when using this liquid. It is much costlier than mineral oil and makes the initial cost of the transformer higher. Figure II-6 shows the process for PFAME making.

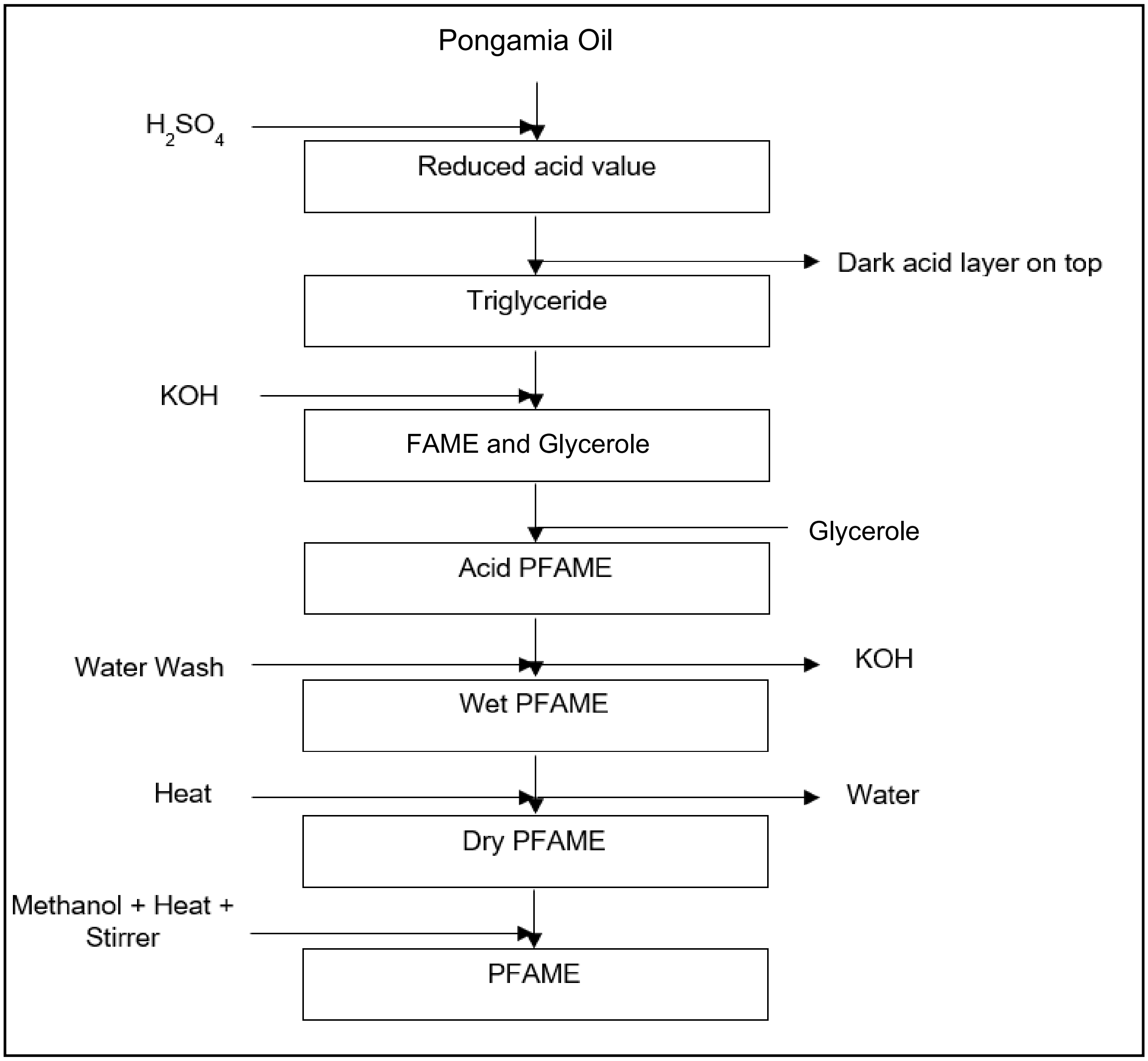

Figure II-6: Block diagram of the process of Pongamia Fatty Acid Methyl Ester (PFAME) [57].

The composition of natural esters varies from a blend of suitable seed oils (e.g. soybean, rapeseed, sunflower) or palm oil plus some additives. It is sourced from renewable resources; natural esters are principally available in large quantity to meet future demands. Different fatty acids that can be polyunsaturated, monounsaturated or saturated is part of natural esters. The composition varies from manufacturers to another as they used different ratios to reach different properties. An example of rapeseed based natural ester insulating liquid is derived from rapeseed fluid extract, with a typical fatty acid composition of 62% of oleic acid, 22% of linolenic acid, 10% of linoleic acid. Another example is soybean-based natural ester insulating liquid derived from a soybean seed fluid extract, with typical fatty acid composition: 24% of oleic acid, 54% of linoleic acid, 7% of linolenic acid [56].

An adequate mixture of various acids is required as saturated fatty acids can be very viscous. Also, unsaturated fatty acids are prone to oxidation. So, an appropriate mixture is required as oxidation stability and acceptable viscosity must be taken into consideration to make these esters applicable as an electrical insulating liquid. Figure II-7 shows different compositions of ester liquids which have been investigated in [44]. A distinction is made between saturated and monounsaturated and polyunsaturated fatty acids. A high proportion of saturated fatty acids favour chemical stability but leads to a high-freezing point. The higher the proportion of triple-unsaturated fatty acids (linseed / tung fluid), the more unstable the oil becomes in the air. Unsaturated fatty acids have the property of remaining liquid at low temperatures. The most common monounsaturated fatty acid in vegetable oil is oleic acid with 18 carbon atoms. According to the general nomenclature, this is called C18: 1 [38]. The first number represents the number of carbon atoms, and the second level of unsaturated fatty acids. Table II-3 gives an overview of the fatty acid composition of some oils and fats [58]. HO stands for High Oleic and SO for sunflower oil.

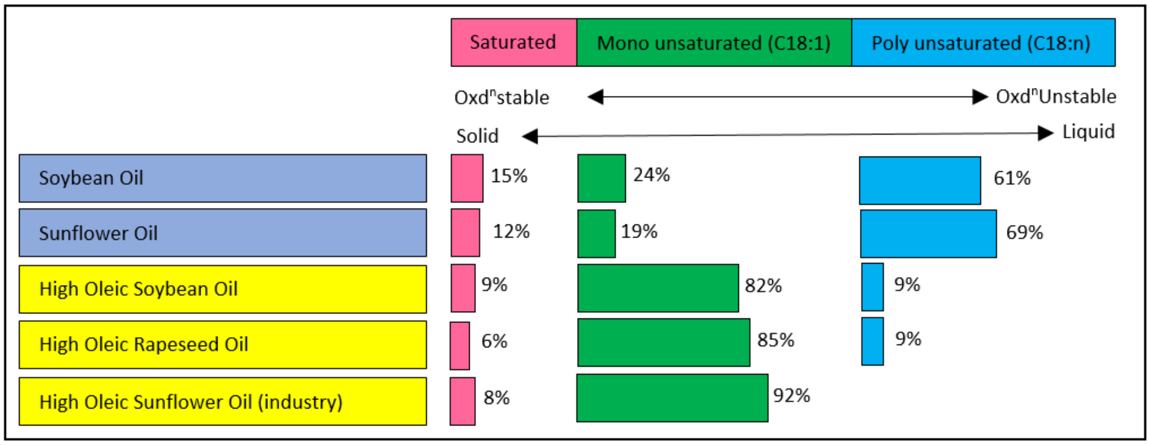

Figure II-7: Overview of fatty acid composition of some oils and fats [44].

Table II-3: Different types of acid found in ester [59]

	Oleic acid C18:1	Linoleic acid C18:2	Alpha - linolenic acid C18:3	Stearic acid	Palmitic acid
HOSO	80-92%	3-10%	0%	1-4%	4%
HO-Raps	75-85%	6-10%	3%	1-2%	4%
HO-Soja	75-82%	9-11%	1,5%	2-3%	6%
Olive oil	73-78%	9-11%	0,5%	3-5%	10%
Palm oil	36-40%	10-12%	0,3%	4%	44%

Depending on mixture ratio between saturated and unsaturated acids, different additives are added to reach an appropriate pour point and oxidation stability. To be compliant with Organisation for Economic Co-operation and Development biodegradation, the total content of the additive is normally lower than 2%. The maximum permissible additive weight fraction is 5% according to IEC 62770. The insulating natural ester available on the market has different values for pour point and oxidation stability. As an example, a better oxidation stability is obtained for saturated sunflowers than soybean fluids because of their high content of oleic acids [60]. In both cases, they are not going to be used in free breathing equipment. Oxidation for natural esters in breathing conditions will push liquid toward accelerated polymerization of the unsaturated acids and it will cause a huge increase in viscosity ending in jelly or solid state. At this stage, it will clog the paper as it adsorbs on the surface of the solid insulation and the transformer will be required to be shut down for related maintenance activity. Different additive such as PMMA can be added to depress the pour point. The oxidation stability of natural ester fluids can be enhanced further by adding two or more antioxidants [61].

2.3.6 ADVANCES ON ESTER DIELECTRIC FLUIDS

Numerous studies since the 1990s have warranted the performance of these new insulating fluids compared to traditional mineral oils. Researchers examined the research results and the performance of these new fluids. In early 1998, T.V. Oommen declared ester dielectrics fit to be used in electrical insulation systems [62]. Most researchers now are in favour of using these new fluids as a potential replicate for mineral oil. Substantial analysis reports focusing on the investigation of synthetic and natural esters versus mineral oils are summarized in Table II-4.

As the new fluids have not been on the market for a long period of time, many researches are required to assess the conditions of aging and degradation compared to mineral oil. As the industry is very conservative, it is difficult to change the mind of the owners as they require a proven technology installed in many sites. As there is not much research done in this field yet, as compared to mineral oil which is a century-old proven technology, research needs to be pushed to develop condition monitoring methodologies, breakdown voltage, pre-discharge phenomena, miscibility, and retro filling for the new fluids. Additionally, the performance of these new fluids in cold countries such as the north of Canada is not seen much in the literature.

Ester fluids are not well known for their performances and their regeneration methods. Some aspects to stimulate its use in the industry needs to be exploited. Recent advances in research in general and with emphasis on the aspects discussed above are examined in this section. The feasibility of using various vegetable oils in transformers is a major topic for many researchers. On one hand, it is well known that vegetable oil has a high breakdown voltage and good dielectric properties. On the other hand, the high rate of oxidation of vegetable oil is a concern. Palm fatty acid esters (PFAE) have become one of the prevalent vegetables based oils in the field of substitute oils [63].

Table II-4: Summary of significant reviews reported in the literature on ester fluids for use in transformers insulation system

Ref	Year [*]	Highlights of review
[64]	2012	The authors summarized the physicochemical, electrical and environmental properties of commercial ester fluids (natural & synthetic), silicone oils, mineral oils and some vegetable oils.
[36]	2015	The authors highlighted the manufacturing process and usage of various vegetable oils in transformer applications. Critical properties and performance of vegetable oils are summarized in comparison to mineral oils. Discussions were confined only to various vegetable oils that are available across the globe.
[33]	2016	Various properties of oils were comprehensively reported while focusing on the corresponding literature and standards addressing the oil properties. Authors confined to the survey only to natural esters and mineral oils.
[65]	2016	Advantages and challenges in adopting natural esters for transformer insulation technology were highlighted. Authors confined to the survey only to natural esters and mineral oils while enumerating the challenges in the transformer materials and designing for natural ester filled transformers. No incompatibilities have been found among natural ester liquid and material typically used with conventional mineral oil.
[66]	2016	The research progress associated with the physicochemical, electrical properties of ester fluids (natural & synthetic) was discussed. The feasibility of using Pongamia Pinnata oil in distribution transformers has been also investigated in comparison to mineral oil.
[67]	2015	The properties of commercial ester fluids (natural & synthetic), mineral oils and some vegetable oils are summarized along with a critical literature survey. The authors reported the deterioration of ester-based oil/paper insulation vis-à-vis mineral oils.
[30]	2019	The authors identified the aspects of the usage of ester fluids in transformers listed below : • The miscibility and retro filling aspects of the new insulating oils; • The workability of ester fluids in regions with cold climates; • The application of ester fluids in on-load tap changers (OLTCs); • Pre-breakdown phenomena of ester fluids; • Environmental performance and fire-related aspects.

[*] *The year until which detailed published literature is considered for review.*

J. Tokunaga et al. explored the efficiency and useful life of solid insulation in PFAE (palm fatty acid ester) filled transformers [68-70]. It was deduced that lifetime of solid insulation in PFAE is between 6.1 to 7.3 times (according to criteria) longer than life-time mineral oil. McShane and his team evaluated the tensile strength of insulation paper at different temperatures with natural ester fluid and showed that ester fluids actually improve thermal stability of the paper as moisture is absorbed from it thus extending its life [71, 72]. Esters fluids are more hygroscopic than mineral oil and tends to draw moisture from the paper which increases its tensile strength and reduce the rate of degradation [73].

Performance analysis of Karanja oil [74], edible oils [75, 76], camellia and rapeseed oils [77], and waste vegetable oil [78] was reported lately and the advantage of vegetable oils over mineral oils and viability of this oil for use in transformers was emphasized. Condition monitoring information of in-service vegetable oils for a transformer in operation was documented for 10 years in [79]. This condition monitoring data include important parameters like dissolved gas analysis, acid number, dissipation factor, interfacial tension, water in oil, and dielectric strength. It was found that natural ester generates similar traces of dissolved gas as mineral oil but with higher concentration of ethane. Also, the sealing of natural ester filled transformer was more effective to sustain longer service periods as it is very sensitive to oxygen.

Several utilities started using natural ester in their sealed transformers due to their characteristics [80]. Natural ester is performing well in sealed transformers with the oxidation, whereas it is questionable for breathing transformers. Some researchers investigated to improve the oxidation stability of natural ester. Different proportions of numerous antioxidants were tested along with the effect on aging indicators. Different oil properties have been correlated for various proportions of three antioxidants: butylated hydroxy toluene (BHT), butyalted hydroxy anisole (BHA) and gallic acid (GA), which were investigated to trace oil properties. It was found that the trend is similar to mineral oil, and that the addition of more antioxidants to natural ester reduces the breakdown voltage [81].

In [82], authors demonstrated an optimal calculation method to determine the concentration of inhibitors required to improve the oxidation stability for transformers filled with natural esters and maintain an appropriate dielectric strength. It was reported that the rate of degradation of pressboard in natural esters is originally faster than that in mineral oil. In [30], authors stated that the hydrolytic degradation rate of the pressboard in mineral oil becomes important after reaching half-life, but that the rates of degradation slow down with aging in natural esters. It was explicated that esters consume more moisture during hydrolysis and upkeep the dryness of solid insulation, so that the aging of cellulose is slowing down. It is also cited that the hydrolytic deterioration of natural ester-based oil/paper insulation has only a minor impact on oil viscosity. Degradation of paper oil complex insulation is largely associated with colloidal particles and soluble particles. These decay particles with moisture have an aggressive role in reducing the dielectric strength of oil.

It is already well established that the rate of degradation of cellulose insulation paper is slower in ester fluids as compared to mineral oils [73]. The same was explicitly verified through direct paper characterizations by subjecting ester-based oil/paper insulation to vigorous thermal aging [83-89]. Direct measurements like degree of polymerization, moisture on paper, cellulose crystal size, relative crystallinity of cellulose, and expansion/shrinkage properties of cellulose pressboard, as well as tensile strength, furan analysis and molecular properties, were reported. It is inferred that esters arrest the deterioration rate of cellulose insulants and thus prove superior in terms of cellulose degradation index as compared to mineral oils under the same laboratory conditions.

2.3.7 RETRO FILLING AND MISCIBILITY

Mineral oils and ester fluids can be mixed in any proportions as they are miscible. The challenge for the mixture use in transformers is to study the performance of mixed oil and find an optimal proportion. As ester has a better performance than mineral oil, using a mixed fluid it is expected to be more efficient than mineral oil alone while being cheaper than ester. Fofana et al. in 2002 reported on various proportions of mineral oil and ester oil to find an optimal mix according to the dielectric properties, moisture behaviour and insulation paper [90]. Perrier et al. reported that the addition of a quantity of esters to bulk mineral oil improves the performance of the mineral oil. Perrier also cited the lack of standard procedures for mixing oils [43]. There is no consensus yet, but results show that a ratio of about 20% of synthetic ester to 80% of mineral oil is an optimal mixture. In fact, dielectric strength is greatly improved, reducing the statistical risk of a malfunction by insulation breakdown [91]. Thermal expansion, thermal conductivity, viscosity, density, and specific heat were investigated for various proportions of synthetic ester and mineral oil in [92]. It is also stated that the fire and environmental properties of mineral oil could also be enhanced with the mixing with esters. Stability analysis of mixed oil by electrical, breakdown and thermal stressing are presented in [45]. It is observed that oil absorbance and pressure varied proportionally with the addition of esters. The researchers are interested to investigate long-term ageing as well. The mixed blend of 20% of synthetic ester and 80% of mineral oil was also investigated on oxidative ageing for different properties such as absorbance, dissolved decay products and interfacial tension. It was demonstrated that the addition of esters slowed down the rate of deprivation of mineral oil significantly [14]. Retrofilling a transformer operating originally with mineral oil with ester fluid will decrease the cellulose moisture content and hence rate of aging. The process of retrofilling is to be completed within a regular shift of work in 7 hours by the employees to avoid the adsorption of solid insulation [93].

2.3.8 ENVIRONMENTAL AND EMISSION PROFILE

Nowadays, selecting the appropriate fluid is not only a matter of technical performance, material selection and cost but also a question about overall environment and total lifecycle cost. One of the major concerns of today's society is about renewability and biodegradability of material, including fluids used in the transformers. By using renewable and biodegradable fluids, it is supporting environmental regulations in case of fire accidents or spillage. Alternative oils should not be hazardous and should go alongside with environmental regulations. The minimum health and environmental related requirements for using a liquid as a dielectric fluid are listed [94]: non-toxicity, biodegradability, acceptable and low-risk thermal degradation byproducts, recyclable and readily disposable.

When a spill happens, mineral oil will act as a pollutant to the environment compared to natural ester which is fully biodegradable. The biodegradability is the measure of biological oxygen demand (BOD). BOD represents the amount of oxygen consumed for the bacteria and other microorganisms for digesting with resulting biodegradation [95]. Hence, a higher amount of BOD indicates higher biodegradability of the fluid. The presence of a sufficient concentration of dissolved oxygen is critical to maintaining the aquatic life and aesthetic quality of streams and lakes. The emission profile is a marker related to the environmental performance of the insulating fluid. The emission profile of an insulating fluid reveals the nature and type of the emitted gases and the behavior of the flames when the fluid is exposed to combustion [30].

2.4 DISSOLVED GAS ANALYSIS

The use of Dissolved Gas Analysis (DGA) as a method to determine the types of pending or occurring faults within power transformers has been in practice for many years. DGA techniques have become standard practice as part of normal maintenance for few electricity power utility companies. The critical aspect of fault gas analysis is the right diagnosis of the fault generated by the detected gases. Many methods exist to interpret these gases [96].

Some of the hydrocarbon bonds can break down and form free radicals such as H^*, CH_3^*, CH_2^* and CH^*. These breaks are due to several constraints, including the source of the energy required to break covalent bonds at the molecule level.

All these radicals can recombine to form fault gases observed in the fluid:

$H^* + H^* \rightarrow H_2$ (hydrogen) (2.1)

$H^* + CH_3^* \rightarrow CH_4$ (methane) (2.2)

$CH_3^* + CH_3^* \rightarrow C_2H_6$ (ethane) (2.3)

$CH_2^* + CH_2^* \rightarrow C_2H_4$ (ethylene) (2.4)

$CH^* + CH^* \rightarrow C_2H_2$ (acetylene) (2.5)

In addition to these gases, the decomposition of paper will produce CO_2, CO and H_2O, due to the presence of oxygen atoms in cellulose molecules. In addition, furanic compounds will be present if the cellulose is decomposing. Due to the lack of specificity of carbon oxides and the lack of sensitivity of 2-FAL to determine the condition of the paper in the case of thermostable papers, other molecules derived from the degradation of the paper are actively studied such as methanol and ethanol in order to estimate the degree of polymerization of the paper and also to estimate the remaining life of the transformers [97].

2.4.1 SAMPLING FOR THE DECOMPOSITION GAS ANALYSIS

An oil sample is taken from the equipment for the analysis of dissolved decomposition gases. The extraction sampling should take place without air contact as far as possible to prevent contamination with atmospheric gases and the loss of poorly soluble gases (especially hydrogen). Gas-tight glass syringes are suitable for sampling. If free decomposition gases arise in the event of a fault, these can be removed directly from the Buchholz relay using a glass syringe.

2.4.2 DUVAL TRIANGLE

The Duval Triangle uses a triangular representation of three hydrocarbons: CH_4, C_2H_4 and C_2H_2 in term of relative proportions from 0 to 100% of the three gases.

These three gases correspond to the increasing levels of energy necessary to generate gases in transformers in service. The triangle method is illustrated in Figure II-8. There are 6 faults and a mixed fault (electrical and thermal (DT)) represented in Table II-5 (PD, D1, D2, T1, T2, T3 or DT). Different types of fluids will have their own boundary area in the triangle according to the results taken from the empirical tests.

For high energy faults (like arcs), C_2H_2 and C_2H_4 are used in all analysis methods and high temperature faults.

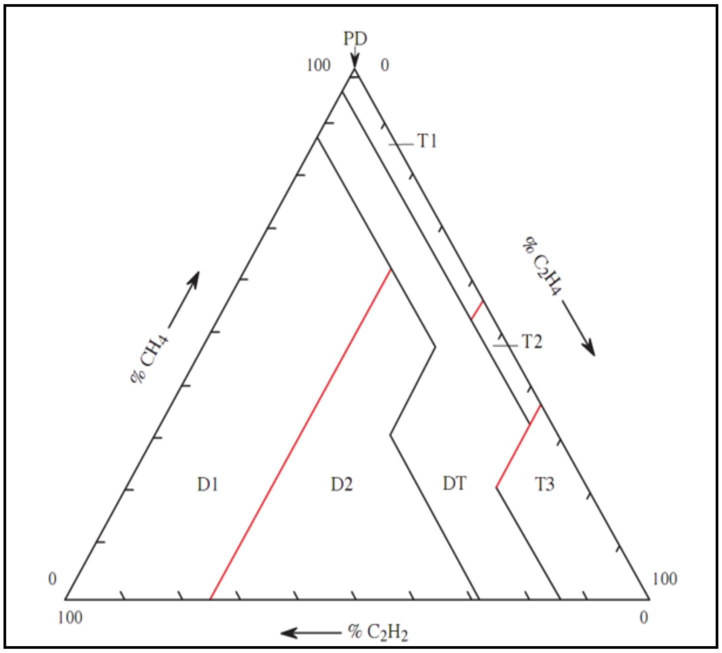

Figure II-8: Duval triangle 3 for midel synthetic ester [98].

Table II-5: Example of faults detected by Duval Triangle[98]

Symbol	Fault
PD	Partial discharges
D1	Low energy discharges
D2	High energy discharges
T1	Thermal fault T<300 °C
T2	Thermal fault 300 °C <T<700 °C
T3	Thermal fault T>700 °C
DT	Mixtures of faults

2.4.3 DUVAL PENTAGON

The Duval pentagon is similar to the Duval triangle. The pentagon uses five (5) gases instead of the three (3) ones used by the triangle. [99]. The five main hydrocarbons used are H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2.

The pentagon method is presented in Figure II-9.

There are 7 faults represented in Table II-6 (PD, D1, D2, T1, T2, T3 or S).

The Duval pentagon may be used by itself as the Duval triangle, and it is not intended to replace the Duval triangle for oils. Rather, it is intended to reveal complementary information.

Different types of fluids have their own boundary area in the pentagon according to results x from the empirical tests.

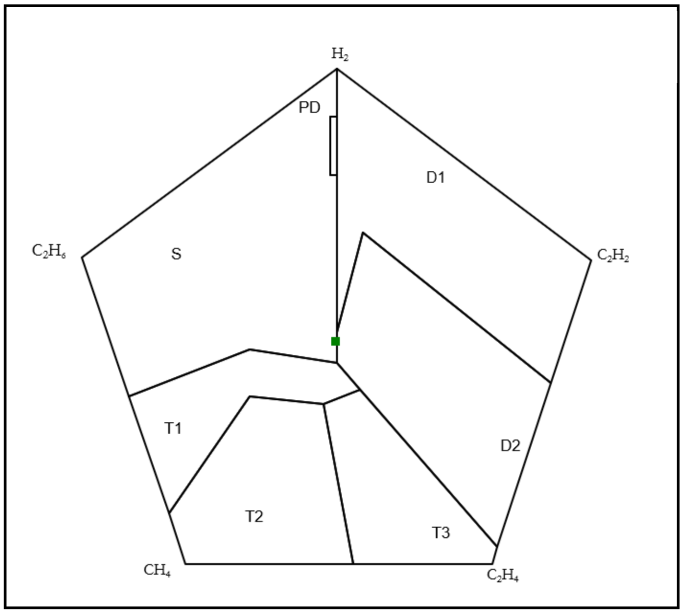

Figure II-9: Pentagon 3 method for midel synthetic fluid [99]

Table II-6: Example of faults detected by Duval pentagon [99] [100]

Symbol	Fault
PD	Partial discharges
D1	Low energy discharges
D2	High energy discharges
T1	Thermal fault T<300 °C
T2	Thermal fault 300 °C <T<700 °C
T3	Thermal fault T>700 °C
S	Stray gassing

2.5 RESEARCH PROGRESS ON VARIOUS FAULTY CONDITIONS

It is to be recalled that the type of gases evolved is dependent on the fault conditions and state of the liquid. Gassing tendency based on the state of the liquid has been the least emphasized in the literature. However, tendencies of liquids based on fault conditions have been an object of interest and they are summarized in this section.

2.5.1 LOW ENERGY DISCHARGE

Partial Discharge (PD) is an electric discharge that only partially bridges the insulation between conductors. A partial discharge may occur inside the insulation or adjacent to a conductor [101]. Electrical discharge within the transformer in the form of low energy is quantified as partial discharge [102].

Wang et al. [103] investigated the gas generated in mineral oil and natural esters for partial discharge and sparking faults. They found that the key gases generated under PD faults are hydrogen and acetylene in both mineral oil and natural esters. This means that they suggested methods for diagnosing PD and sparking faults in mineral oil are applicable in natural esters. They mentioned that the fault gases under PD was 50 times higher for natural esters than mineral oil, and that the total volume of faults gases per unit fault energy is similar for both. Korraya Jongvilaikasem et al. [104] tested gas generation for various partial discharges like corona discharge, surface discharge and internal discharge in natural ester.

- As corona discharge can happen at the tip of conductive material under high electric field, it has been performed with a needle electrode with different tip radius of 10, 20, and 40 micrometres and with a plane electrode with a diameter of 45 mm as the grounded electrode. The gap distance was fixed at 32 mm. The stress was applied for a 2-hour period. Results are presented in Figure II-10.
- Surface discharge was simulated with a 20-micrometer tip radius needle for energized high voltage and the same grounded plate electrode was used. Three groups of pressboard samples were tested, including non-impregnated pressboards and impregnated ones, each for 8 hours and 16 hours. Each pressboard sample was inserted between electrodes. The stress was applied for a 1-hour period. Results are presented in Figure II-11.
- Internal discharge may happen because of contamination of the electrical insulation such as void, air gap, which are vulnerable points under the electric field.

- The setup for internal discharge consists of a plane-plane electrode with a diameter of 45 mm. Three groups of pressboard samples were tested, including non-impregnated pressboards and impregnated pressboards each for 8 hours and 16 hours. The pressboard sample was inserted between the electrodes. The stress was applied for a 1-hour period. Results are presented in Figure II-12.

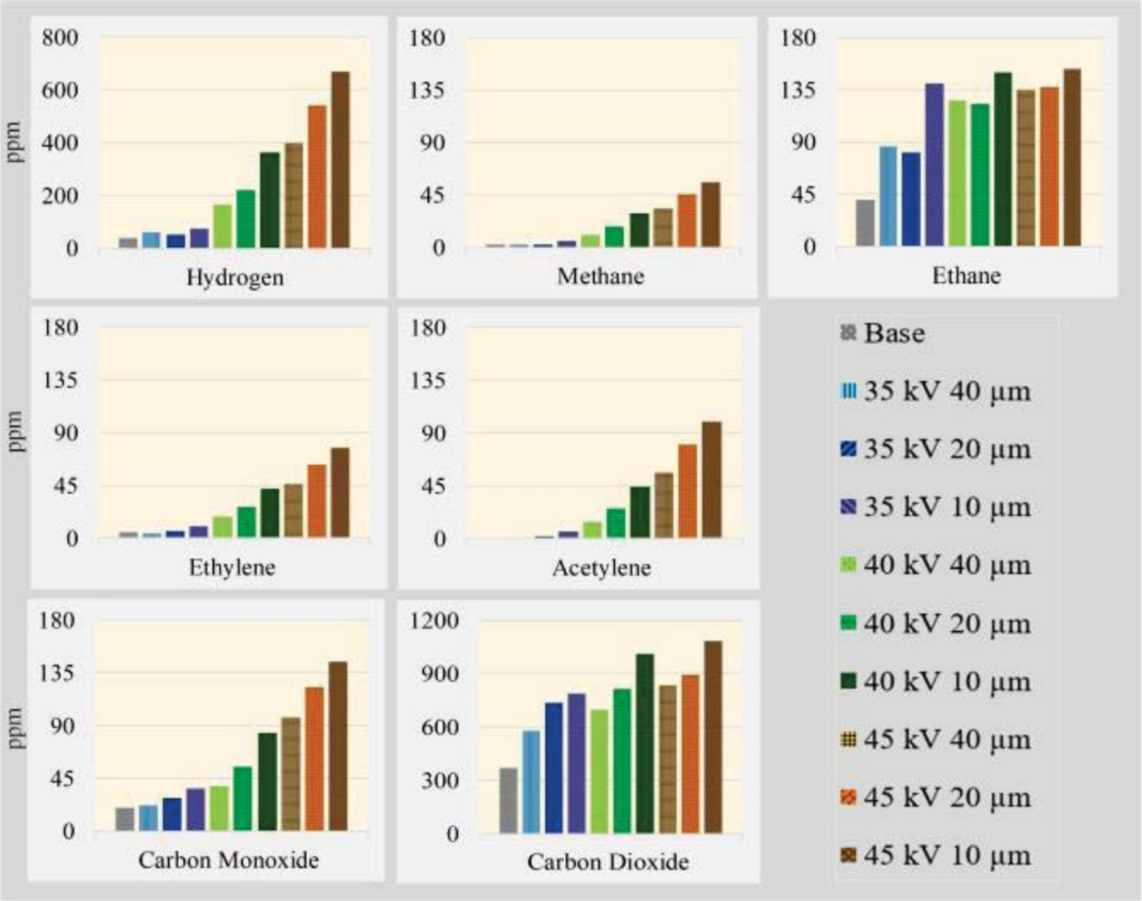

Figure II-10: Dissolved gases generated from corona discharge activities on natural ester with various test voltage levels and tip radii needles [104].

All gases follow an increasing trend as the voltage increases and the radii decrease. For ethane, the increase in gas is highly dependent on the voltage applied. For carbon dioxide, the gas tendency is much more dependent on the radii than the voltage applied. For hydrogen, methane, ethylene, acetylene and carbon monoxide, the gassing tendency increases exponentially while the voltage increases and the radii decrease.

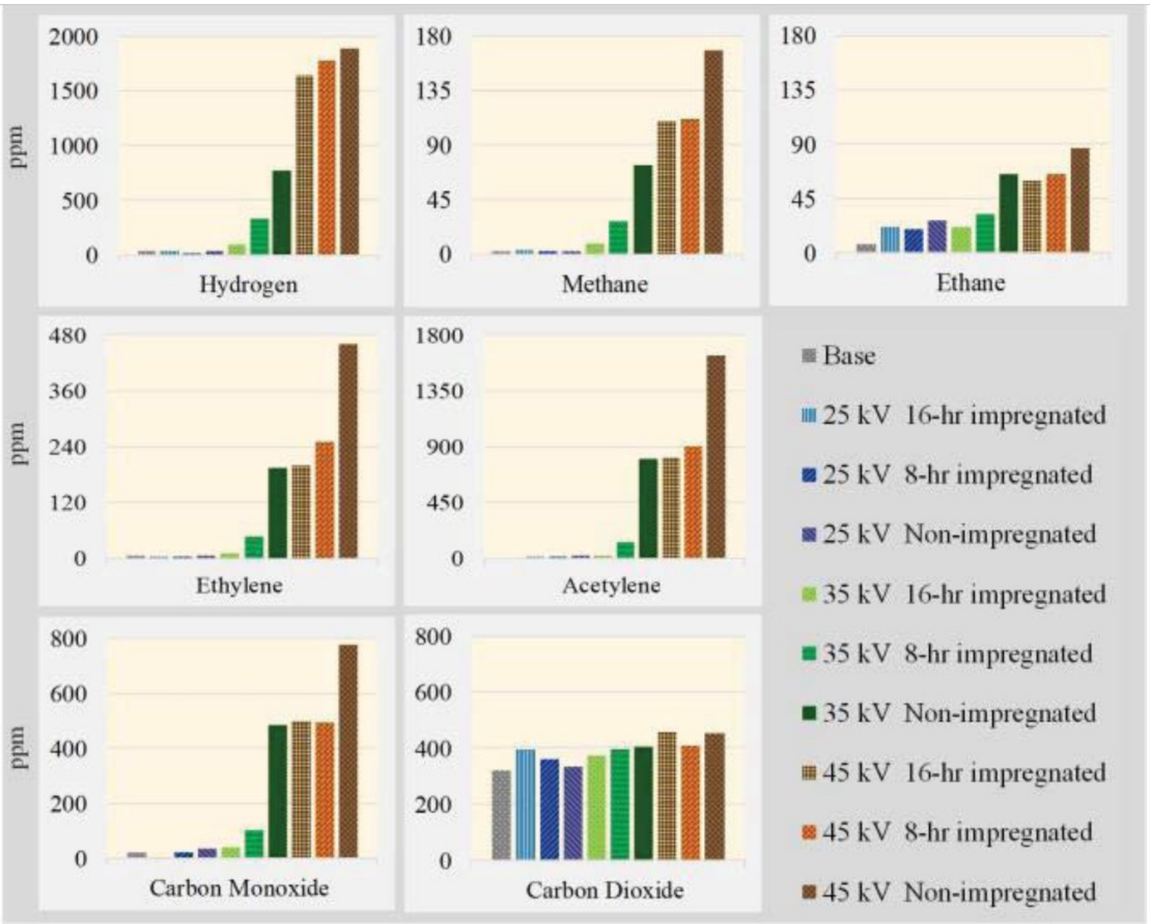

Figure II-11: Dissolved gases generated on natural ester by surface discharge activities [104].

In general, there is an increase in gassing tendency when the ester in non-impregnated pressboards compared to an impregnated pressboard. Only carbon dioxide does not show major increase/change over time.

Most gassing tendency were pretty stable except for 45-kV non-impregnated pressboard. In fact, all gases for this particular sample increased for this particular experiment.

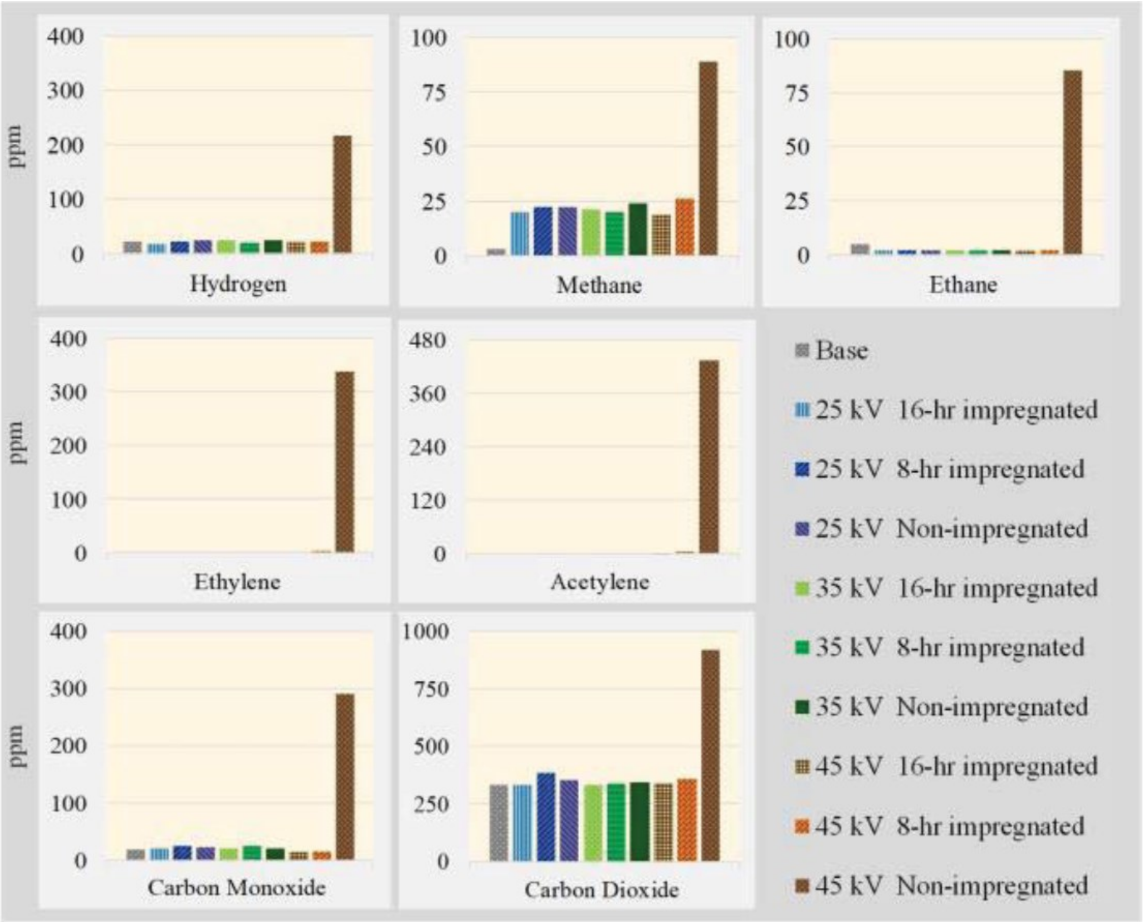

Figure II-12: Dissolved gases generated on natural ester from internal discharge activities [104].

Fault gas generation behaviour of alternative dielectric fluids (soy seed-based oil) and mineral oil as reference under partial discharge, arcing and overheating were assessed at different moisture levels [105]. It was observed that the key gases for mineral oil and ester based were changing as the moisture level changed. The level of gassing for esters was a lot lower than mineral oil for all the tests except for ethane on the overheating test. The quantities and the tendency of dissolved gases for faults in soy seed-based oil was contrasting with the mineral oil. Only a small quantity of gases was released from the soy seed-based oil from the partial discharge. The main key gases produced were dissimilar for the mineral oil and the soy seed-based oil. As the gassing quantities and trend are different, the standardized tools for mineral oil are not applicable to soy seed-based oil.

Another research [106] has verified low energy electrical faults and thermal stray gassing faults in laboratory environments for mineral oil and ester fluids and established lower gassing tendency of ester fluids. For electrical faults and more specifically for low energy discharge, the same gases (hydrogen and acetylene) are created in the fairly same ratios for mineral and ester oils. It was demonstrated that classic Duval triangle 1 is fairly relevant for this type of fault validating the results in the literature. For thermal faults and more specifically for stray gassing (low thermal faults), ethane in association with hydrogen are the key gases of natural esters. For low temperature faults and paper faults in mineral oils, Duval triangle 4 is the appropriate tool. For low temperature faults in FR3, Duval triangle 6 works properly. All triangles work well for mineral and ester fluids.

Imad et al. [107] examined the impact of alternative fluid on DGA. Mineral oil, synthetic esters and natural esters were taken for analysis. These oils were aged at 90 °C for 3 days, at 150 °C for 14 days, and at 200 °C for 1 hour. These samples were analyzed as follows:

- Low energy arc test was performed on the samples for a series of 20 breakdowns. A 220 V/40 kV, 8 kVA test transformer was used to generate a breakdown across the needle to plane electrode configuration with an oil gap distance of 15 mm.
- Partial discharge was performed using the same circuit as a low-energy arc test. A water resistor was added in order to limit the current.

Despite the fact there is huge difference in the molecular structure of esters compared to mineral oil, the gases generated by different thermal and electrical faults are not different from the mineral oil's behaviour. The rate of production of dissolved gases in esters is not as much as that of mineral oil. Under thermal faults of medium temperature range, however, esters are exceptionally stable. The large generation of ethane under thermal faults for FR3 fluid suggests it could be used as a key indicator in combination with ethylene. Carbon monoxide and carbon dioxide are still key indicator gases for cellulose degradation simulated by the thermal tests in mineral oil and esters.

Acetylene is the key gas for low energy electrical faults, and hydrogen is the key gas for partial discharges. Even in electrical faults ester generates less gas compared to mineral oil. For both types of fault, the small quantity in the total gas generation will make the identification of the problem more challenging at an initial phase in practical applications. The Duval triangle is providing an appropriate diagnostic in the thermal faults in all three fluids: mineral oil, synthetic ester and natural ester. For the esters, the temperature range of the fault is overestimated.

Most of the tests performed under the IEC techniques were successful for thermal faults except natural esters mixed with paper at 200 °C as not enough methane was produced, and no result of fault was found. The synthetic esters mixed with paper produced an overestimation of the temperature of the fault.

Low-energy discharges for electrical faults were correctly diagnosed under all methods. Significant quantity of hydrogen is generated in all cases for corona discharges, unfortunately only the IEC techniques provided correct diagnosis. The fingerprints on DGA for esters and mineral oils are the same, but the criteria of faults gas ratio need to be redefined to provide correct diagnosis. In order to compare the gassing tendency for mineral oils and ester fluids, they were put under partial discharge or low energy discharge in [106, 108, 109]. The key indicator remained C_2H_2 even if the quantity in natural esters was increased for this last one and for H_2 as well.

2.5.2 HIGH ENERGY DISCHARGE

Discharges of High Energy (D2) – occurs in oil and/or paper, as indicated by extensive destruction and carbonization of paper or metal fusion at the discharge extremes, extensive carbonization in oil, and in some cases, tripping of the equipment confirming a large current follow-through [96].

High-energy discharges are mainly due to arcing caused by short-circuiting faults and winding deformations. These discharges involve the excessive generation of hydrogen and acetylene with traces of methane and ethylene. If this fault occurs in cellulose insulants, carbon monoxide and carbon dioxide will also be traced. High-energy discharges are detrimental to the insulation system [110]. High-energy discharges are also associated with high temperatures that may cause premature thermal degradation of oil/paper insulation. Also, the influence of high energy discharges on the gassing tendency of the dielectric fluids have been reported in [108, 111, 112]. Similar to the low energy discharge faults, H_2 and C_2H_2 are found to be witnessed due to arcing fault conditions. However, a large amount of C_2H_2 is generated as compared to the low energy discharge cases.

Chenmeng Xiang et al. [111] tested gas generation in mineral oil and vegetable oil under typical electrical and thermal faults. It was found that a large amount of C_2H_2 is generated under high energy electrical breakdown both in vegetable insulating oil and mineral insulating oil, which shows that the main dissolved gases under electrical breakdown in these oils are the same.

2.5.3 THERMAL STRESS (HOT SPOT)

The Hottest point in a transformer winding, usually referred to as the hot-spot, determines the loadability and lifetime of the transformer [113] [114].

The gassing tendency of ester fluids under simulated thermal fault condition were also explored and are reported in numerous publications such as [108, 109] [111] [115] [116]. It was found that natural esters generate more gases at a higher temperature (> 300 °C). Also, as the temperature increases, traces of C_2H_6 increases. For thermal faults of ester fluids, it was found that key gases are CH_4, C_2H_4, CO, and C_2H_6. Various methods exist for the simulation of a hotspot thermal faults at different temperatures: the gassing tendency will act accordingly to this stress. The details of which were analyzed and reviewed in [117].

If cellulose insulants are attacked by partial discharge, carbon monoxide and carbon dioxide are released. Hotspots are coming from highly overheating caused by overload operation and internal faults. Temperature rise from hotspots may lead to the deterioration of the insulation and production of gas bubbles [15]. X.F. Wang, et al. [118] tested mineral oil for thermal fault heating using a tube heating method. The total gas generation was tested for 350 ºC, 550 ºC and 750 ºC. Gas generation increased for all the gases. At 350 ºC, more than 60% of the gas generated consisted of methane. As temperature increased, the percentage of methane decreased and that of ethylene increased. Hydrogen and acetylene were generated only at 750ºC.

Przybylek and al. [117] tested gas generation for mineral oil, natural and synthetic esters under thermal faults of 250 ºC, 350 ºC and 450 ºC. In the general gas analysis, propane and propylene are omitted. This should mainly be taken into consideration for synthetic esters as it plays a role for type T2 thermal faults (above 300 ºC). Carbon monoxide and carbon dioxide can be associated in natural and synthetic esters with the presence of oxygen. Carbon oxides are present (in mineral oil it is associate to cellulose disintegration), in ester liquids, but it is not always associated with the degradation of cellulose. For a temperature of 450 °C, the volume of combustible gases in synthetic esters was more than 11 times higher than in the case of natural esters, but it was more than 23 times higher than in the case of mineral oil with an overheating temperature of 400 °C. In the case of synthetic esters, at a temperature of 450 °C, there were considerably higher volumes of carbon monoxide, methane, ethylene, ethane, propane, and propylene compared to mineral oil and natural esters. It should be noticed that many standards neglect the use of propane and propylene in DGA despite the fact that they are generated during overheating of esters, especially synthetic esters, in significant quantity. The authors consider acceptable to use them, in order to improve the categorization of thermal faults.

Xiang et al. [111] investigated thermal faults on mineral oil and vegetable insulating oils and found what follows :

- The main gas obtained after overheating is CH_4 in mineral oil whereas C_2H_6 in FR3, and H_2 and C_2H_6 for camellia insulating oil. The presence of insulating paper significantly increases the amount of CO and CO_2 in dissolved in oil.

- As temperature increases, the percentage of the main dissolved gases increases. The percentage of CH_4 and C_2H_4 increases as the temperature increases in mineral oil; the percentage of C_2H_6 increases as the temperature increases in FR3 oil; the percentage of H_2 increases while the percentage of C_2H_6 fluctuates with the increase of temperature in camellia oil.

The authors confirmed that the tools used to diagnose the mineral oil were not fully appropriate to deal with electrical and thermal faults in vegetable oils. Comparative analysis of fault gas generation for mineral oil and natural esters under thermal fault conditions has been reported in [119]. The thermal stability of natural esters is better than mineral oil, which is assessed by the quantity of gases generated and their behaviour above 300 °C. The amount of faults gas increases roughly exponentially with temperature increase for the mineral oil and natural esters. The key gases for natural ester (FR3) under thermal faults are C_2H_6 and carbon oxides at 300 °C and 400 °C, because of its nature as a type of triglyceride fatty acid ester. The key gases for mineral oil (Gemini X), are CH_4 at 300 °C and CH_4 and C_2H_4 at 400 °C. For natural esters and mineral oil, C_2H_4 and C_2H_2 start to appear at higher temperatures and increased significantly with localized heating. The higher the temperature, the smaller the CO_2/CO ratio which applies to both fluids. C_2H_6 and C_2H_4 are increasing in percentages and CO_2 is decreasing in percentages for FR3 as the temperature increases. Duval triangles were used and there are some misinterpretations in the results because of higher percentage of CH_4.

2.6 ECONOMICS AND MARKET EVALUATION

The quantity of fluid for a transformer depends on its size, capacity and design. For example, a pole of 3 transformers units of 167 kVA each in Québec for a total capacity of 500 kVA. Each transformer containing a quantity of approximately 250 to 300 liters of fluid. For pad mount distribution transformers of 315 kVA to 2000 kVA contains approximately from 300 to 1200 liters of fluid. A large transformer operating on the 735kV can contain up to 212000 liters of fluids [120].

Large units on the transport grid take a lot of oil to insulate up to 765 kV for a large capacity of hundreds of MVA. Only for Hydro Québec there are 534 substations on the transportation grid, requiring a large quantity of oil [121].

With this large quantity of oil in service just in the province of Québec, the quantity of dielectric fluid internationally on the entire grid is immense. All the transformers installed across the globe have this need of fluid from the mineral oil. By replacing the mineral oil by a renewable source with better properties as dielectric fluid for transformers across the globe, it indicates that the potential of the market for ester-based dielectrics is massive.

Although the 10 to 15 percent extra cost of ester-filled transformers compared to mineral insulating oils is more desirable properties and can extend the life of the transformers [122]. It is a green fluid as it will not create damage to the environment compared to mineral oil in case of a leak. As the high cost compared to mineral oil is a barrier for small utilities to start using ester dielectrics. Even though the direct cost of esters is higher than mineral oil, the overall cost of ownership of the transformer is going to be cheaper as esters have better properties to extend life and these properties more than offset the additional cost of ester fluids [123]. Furthermore, synthetic ester that has a high fire point which is significantly increasing the fire safety of transformers and reducing the need for fire protection equipment [124].

A major criterion of any industry to accept a new technology is cost evaluation or payback. McShane and his team described the usage of ester oils that reduce the total life cycle cost for transformers [125]. They examined the physical properties of kraft paper aged in ester oil and mineral oil and assessed its ageing behaviour. The detailed list of different parameters of various ester based dielectric fluids can be found in Table II-7.

Table II-7: Comparison of properties and experiences of various insulating fluids [67]

Property	Mineral oil	Synthetic ester	Natural ester	Coconut oil	Sunflower oil
General properties					
Source	Crude Petroleum	Chemical synthesis, Natural synthesis	Natural/ vegetation	Crude coconut	Sunflowers
Cost	Increasing with reduced availability	Marginally costlier than mineral oils	Moderate	Moderate	Moderate
Miscibility	Miscible in all proportions	Miscible in all proportions	Miscible in all proportions	Miscible in all proportions	Miscible in all proportions
Suitability of usage in cool countries	Acceptable	Acceptable	Questionable	Not acceptable	Questionable
Electrical properties					
Breakdown voltage(kV) ASTM D1816	55	79	83	60	38–45
Dielectric constant IEC 60247	2.4@25 °C 2.4@90 °C	3.0–3.5 @20 °C 2.8–3.0 @90 °C	3.3@25 °C 2.8 @90 °C	2.79@20 °C	3.1@25 °C
Dissipation factor (%) ASTM D924	0.02@25 °C 0.09@90 °C	0.0006 – 0.001@25°C 10^{-4} – 0.03@ 90°C	0.08@25 °C 0.64@90 °C	0.08@20 °C 0.005@90 °C	0.0093@25 °C
Resistivity(Ω-m) ASTM D1169	10^{13}	10^{13}	10^{13} to 10^{14}	--	--
Chemical properties					
Chemical type	Hydrocarbons	Acids and Alcohol	Fatty acids	Fatty acids	Fatty acids
Type of liquid	Naphthenic/ Paraffinic	Diester, dimer acid ester, etc.	Ester	Ester/vegetation	Ester/ Vegetation
Antioxidants	Required	Required	Strongly required	Strongly required	Strongly required
Absorbance (Abs) ASTM D6802	0.02213	0.09674	0.02973	--	--
Oxidation stability	Acceptable	Acceptable	Questionable	Questionable	Questionable
Gassing tendency (μl/min) ASTM D2300	−10 to +24	+19 to +30	−22 to −80.5	--	−52.7
Biochemical oxygen demand (ppm) 5-Day SM5210B	6	24	250	--	--
Biodegradability (%)	<30	80	97 to 99	97 to 99	97 to 99
IEC 61039 classification	Not biodegradable	Fully biodegradable	Fully biodegradable	Fully biodegradable	Fully biodegradable
Toxicity	Yes	Low	No	No	No
Health and Safety	Unacceptable	Questionable	Acceptable	Acceptable	Acceptable
Sustainability	No	Yes	Yes	Yes	Yes

Table II-7: Comparison of properties and experiences of various insulating fluids (continuation) [67]

Property	Mineral oil	Synthetic ester	Natural ester	Coconut oil	Sunflower oil
Physical properties					
Colour ASTM D1500	Colourless/ Transparent	Colourless/ Transparent	Pale yellow	Colourless	Pale yellow
Density(kg/m^3) @20 °C ASTM D1298	0.83 to 0.89	0.90 to 1.00	0.87 to 0.92	0.917	0.919
Viscosity(cSt) @40 °C ASTM D445	3.0–16.0	14–29	16–50	29	40–45
Interfacial tension (mN/m) ASTM D971	40–45	35-39	36	--	--
Acidity (mgKOH/g) ASTM D974	0.01	0.06 to 0.2	0.02	0.02	0.02
Pour point (ºC) ASTM D97	−30 to −63	−40 to −60	−10 to −33	20	–18
Flash point(ºC) ASTM D92	110 to 175	250 to 310	310 to 343	225	<330
Fire point(ºC) ASTM D92	110 to 185	300 to 322	300 to 369	300 to 350	<360
Thermal Conductivity (W/m K) @20 °C ASTM D2717	0.135	0.165	0.17	0.16 to 0.17	0.16 to 0.17
Specific heat (kJ/kg K) @25 °C ASTM D2766	1.63 to 2.0	1.80 to 2.30	1.50 to 2.38	--	--
Coefficient of thermal expansion (/°C) ASTM D1903	7×10^{-4} to 9×10^{-4}	6.5×10^{-4} to 10×10^{-4}	5.5×10^{-4} to 7×10^{-4}	--	--
Fire risk assessment class (IEC 61039)	O (fire point 110–185)	K (fire point > 300°)	K (fire point > 300°)	K (fire point > 300°)	K (fire point > 300°)
Emission profile	Unacceptable	Questionable	Acceptable	Acceptable	Acceptable
Availability	Expected to meet crisis in future	Abundant	Abundant	Fair	Fair and season based.

Chapter III

INFLUENCE OF AGEING ON OIL DEGRADATION AND GASSING TENDANCY FOR MINERAL OIL AND SYNTHETIC ESTER UNDER LOW ENERGY DISCHARGE ELECTRICAL FAULTS

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Influence of Aging on Oil Degradation and Gassing Tendency for Mineral oil and Synthetic Ester under Low Energy Discharge Electrical Faults

Résumé

Le but de ce travail est de comprendre l'influence des décharges électriques à faible énergie dans l'huile minérale et l'ester synthétique sur la dégradation des liquides et la tendance au gazage dans différentes conditions de vieillissement (sur la base des valeurs d'acidité). Un défaut électrique de décharge de faible énergie a été créé par une décharge continue de 9 kV pendant une période de cinq heures sur la surface du liquide en utilisant une configuration de laboratoire appropriée. La dégradation des liquides est rapportée en adoptant des mesures de spectroscopie UV, de turbidité et de compteur de particules. La tendance au gazage est comprise par l'analyse des gaz dissous en utilisant les méthodes du triangle de Duval et du pentagone de Duval pour l'huile minérale et les fluides non minérales. Il est à noter que les résultats de l'appareil simulant le défaut dans les liquides ne proviennent pas d'un transformateur en service. Selon les résultats, les gaz de défaut dans l'huile minérale sont impliqués dans des défauts électriques et thermiques accompagnés de gaz parasite alors que seule une activité de décharge partielle est constatée pour l'ester synthétique. On observe que l'influence des décharges de faible énergie sur la dégradation des liquides est plus élevée dans l'huile minérale que dans l'ester synthétique. Il est important de noter que l'existence de défauts de décharge à faible énergie comme les décharges corona impliquera une génération de produits de poids moléculaire élevé en excès par rapport aux produits de faible poids moléculaire qui sont solubles dans le volume liquide.

Abstract

The intent of this work is to understand the influence of low energy discharge electric faults in mineral oil and synthetic ester on liquid degradation and gassing tendency at different aging conditions (based on acidity values). A low energy discharge electric fault has been created by continuous discharge of 9 kV for five hours on the liquid surface using a suitable laboratory setup. Liquid degradation is reported by adopting UV spectroscopy, turbidity, and particle counter measurements. The gassing tendency is understood by dissolved gas analysis using Duval triangle and Duval pentagon methods for mineral oil and non-mineral fluids accordingly. It should be noted that the results from the apparatus simulating the fault in liquids are not from a service transformer. Thus, according to the results the fault gases in mineral oil are involved with electrical and thermal faults accompanied by stray gassing whereas only partial discharge activity is noticed for synthetic ester. It is observed that the influence of low energy discharges on liquid degradation is higher in mineral oil than synthetic ester. Importantly, the existence of low energy discharge faults like corona discharges will involve a generation of excess high molecular weight products as compared to low molecular weight products that are soluble in liquid volume.

3.1 INTRODUCTION

Insulation defects in power transformers are the main cause for most system failures. Insulation defects will generally be caused by impurities and air voids in the insulants. These defects will increase the normal rate of degradation of the insulants. Cellulose paper and mineral insulating liquid furnished the high-voltage engineers with successful transformer insulation system. The defects in the cellulose insulants could be impurities, air in the cellulose capillaries, and moisture in the cellulose fibers. Similarly, the defects in the liquid could be moisture, conducting particles and air bubbles. It should be mentioned that the defects presented here are only in the interest of the present study, i.e., the defects that are responsible to initiate small discharges. Meanwhile, mineral insulating oils are subjected to critiques after successful usage for several decades. The prime reasons for this critique are as follows [34] :

- Non-renewable sources: obtained from crude petroleum stocks.
- Non-biodegradability: effects the aquatic life and is toxic in nature.
- Technical: low flash point, fire point, and requirements of higher breakdown voltages.

The above aspects have been the subject of research for those interested in alternative liquid dielectrics. Several researchers reported the potential of ester dielectric fluids as a possible alternative to mineral oil [126] [127] [128]. However, there is still a great scope for research on understanding the compatibility of these new insulating fluids with transformer operating conditions.

Electrical faults within the transformer may be seen as high energy and low energy discharges. Both of these have different causes and influence phenomena. It is understood that high energy discharges will be associated with high charge concentration (typically that is enough for a breakdown) and lead to severe damages. In case of low energy discharges, the degree of vulnerability will be lesser in the beginning. Nevertheless, these low energy discharges turn as a cancer to the insulation system if not monitored. Low energy discharges initiate from the material defects and design imperfections of the insulation system [28]. Low energy faults if not taken care of, lead to severe consequences that are equal to high energy faults. The phenomenal influence of the presence of these defects are discussed in the subsequent sections of this paper.

Low energy electrical faults will play a proactive role in causing premature aging and degrading the insulation system. In fact, the extent of influence of different faults will be varying largely with the age of the insulation. The influence of electric discharges on the gassing tendency of various liquids has been reported [129]. Authors have reported the influence of corona discharges on gassing tendency of fresh and reclaimed liquids. Comparative analysis of fault gas generation for mineral oil and natural ester under thermal fault conditions has been reported [119]. It is inferred that thermal stability of natural ester is higher than mineral oil, which is accessed by means of free gas bubble formation, violent fluid convection, and behavior above 300 °C. Recently, [117] reported the fault gas generation behavior of mineral oil, synthetic ester, and natural ester for thermal faults at 250 °C, 350 °C, and 450 °C. The detection of propane as a key gas for thermal faults in synthetic ester is established. Fault gas generation behavior of alternative dielectric fluids under electrical and thermal faults have been evaluated and have been previously reported [130] [105] at different temperatures and moisture levels, respectively. Authors reported that fingers print of the fault gases are comparable to mineral oil but with lower gas volumes. Therefore, non-mineral oil diagnosis methods are available for ester fluids. Other research [106] has verified low energy electrical faults and thermal stray gassing faults in laboratory environments for mineral oil and ester fluids and established lower gassing tendency of ester fluids.

The potential key markers to identify the degree of degradation associated with mineral oil-based oil/paper insulation are interfacial tension and acidity [28]. Dissolved gas analysis is also considered to understand the type of fault (if any) that cause premature aging. In this work, acidity is adopted to decide the aging class of the mineral oil and ester [131]. It should be noted that the above discussed aspects are highly interrelated and depends on the molecular properties and type of liquid. Hence, the influence of liquid degradation and gassing tendency at different aging conditions of mineral oil vis-à-vis synthetic ester under different fault conditions will be of high-engineering importance. Degradation of mineral oil and synthetic ester are identified based on acidity values. It should be mentioned that after subjecting liquids to low energy discharge, electric fault degradation is accessed by dissolved decay contents, turbidity, and particle count measurements. It is well established that popular aging markers, interfacial tension, and acidity are in direct relation with the concentration of decay particles and turbidity [28]. This establishment motivated authors in selecting UV spectroscopy and turbidity as diagnostic measurements for the present study. Moreover, particle counts give the change in number of decay particles in liquid caused due to low energy electrical faults. Hence, particle count measurements are also reported in the present study.

In the present paper, the results of the study of the influence of the low energy discharge electric faults on the liquid degradation and gassing tendency of mineral oil and synthetic ester for fresh and aged liquids are presented. Mineral oil and synthetic ester at different aging conditions is subjected to a surface discharge of 9 kV continuously for five hours. Dissolved decay products, absorbance, turbidity, particle counter, and dissolved gas analysis measurements are performed on mineral oil and synthetic ester before and after surface discharge to understand the influence of low energy electric faults on liquid degradation and tendency of gassing at various aging conditions. The gas tendency of the liquids is also reported by measuring the change in pressure of the test cell.

3.2 EXPERIMENTAL SEP-UP

3.2.1 MINERAL OIL AND SYNTHETIC ESTER SAMPLES

Fresh mineral oil (MO) and synthetic ester (SE) are subjected to thermal stressing as per modified ASTM D1934 at 115 °C for 2000 hours. Thermal aging is performed in presence of the copper (3 g/l) and cellulose papers (1:20) in the presence of oxygen. Later, these highly degraded and crushed oil/paper compositions are subjected to sonication for 30 seconds using Qsonica Q1375 Sonicator individually. Sonication helped further crush the degraded paper in insulating liquid and make a gentle blend of highly aged insulating liquid and paper. The blend thus formed from individual liquids is separately transferred into the fresh vacuum degassed mineral oil and synthetic ester at appropriate proportions. This blend added in fresh mineral oil is developed from aged mineral oils, whereas the blend added in fresh synthetic ester is developed from aged synthetic ester. Fresh liquids are subjected to continuous magnetic stirring under vacuum for 48 hours before mixing the blend of degraded liquids and paper. The blended proportions are aimed at bringing new mineral oil and synthetic ester to the desired level of aging factor. Normal aging of insulating liquids may or may not lead exactly to the desired values of aging. Therefore, volume addition of the developed blend (degraded oil/paper) to the liquids with known acidic values is done to achieve desired aging conditions. For reference purposes, the aging factor has been identified based on the neutralization number of the oils. Based on the liquid acidity values the flowing aging classes are obtained as shown in Table III-1.

Table III-1: Acidity details and class of the oil samples [132]

Sample	**Measured acidity (Avg. of two tests)** (mg KOH/g)		
		Class	**NN** (mg KOH/g)
MO 1	0.0819	Prop. A	0.05 – 0.10
MO 2	0.2716	Bad	0.16 – 0.40
SE 1	0.0977	Prop. A	0.05 – 0.10
SE 2	0.24435	Bad	0.16 – 0.40

Therefore, there are three classes (Fresh, Proposition A, and Bad) of insulating liquids that are classified based on the aging factor. These three classes of liquids are used to understand the influence of low energy discharge electrical faults on degradation level and gassing tendency.

3.2.2 LOW ENERGY DISCHARGE ELECTRICAL FAULTS AND SETUP

Low energy discharges in transformer oil/paper insulations are mostly aroused from imperfections in the dielectric medium. These imperfections initiate creepage discharges, which if not monitored culminates into tracking within the insulation medium and leads to a possible breakdown of the insulation system. However, the operating conditions of a transformer lead to several decay products that further intensify the rate of degradation. These decay contents aids in the consequences caused by dielectric imperfections.

Corona discharges in oil/paper insulation is one of the main consequences of the dielectric defects. Intensity of corona discharges is governed by geometry (at the point of discharge), temperature, humidity, gas bubbles, etc. [133] [134]. Under high electric stress, an electric field with high intensity is created within the dielectric medium. The instantaneous distribution of the electric field will not be uniform for a dielectric medium with defects. The most chances for impurities in the insulating liquid and paper medium will be air voids and air bubbles, respectively. The partial discharges are most often and arouse easily from the gas bubble since the permittivity and withstand ability of the gas is lower than the surrounding insulation medium. Therefore, the gas bubble suffers higher electric field intensity than the healthy dielectric medium surrounding it. Thus, this leads to ease of ionization and raises the availability of free electrons for leading the creepage discharges and partial discharges within the paper and insulating liquid, respectively [135]. Similarly, the presence of a conductive particle and moisture will also lead to a discharge. Other causes of partial discharges are the presence of irregular surfaces or sharp angles with the active parts. The field at these sharp edges became locally high, which leads to discharges. Partial discharge in liquids is mostly influenced by the presence of gas or chain of globules at a solid/liquid interface, moisture, and decay conducting particles. In solids, the influencing factors are relatively similar: air voids, humidity, cracks, and shape of the interface zone with the conductor.

Partial discharges in the liquid and paper are accompanied by successive degradation of the dielectric integrity while introducing the decay particles and gases. These decay particles and gases further catalyze the reactions responsible for the insulation system failure. Hence, partial discharging activity in transformers has a high-engineering importance and is to be monitored closely to provide an early warning signal for inspection.

In the present study, a suitable laboratory model is developed to simulate discharge in air on the surface of the liquid (fresh and aged). This surface discharge is achieved by subjecting the high-voltage electrode with 9 kV under AC stress. Firstly, the stress is increased slowly till 9 kV and later maintained for five continuous hours. The schematic of the setup used for the surface discharge is illustrated in Figure III-1. The present setup resembles the standard setup for understanding the gassing stability of the insulating liquids as per ASTM D6180. The changes in the tendency to gassing with stressing time are presented in Figure III-2a) and Figure III-2b) for fresh and aged mineral oil and synthetic ester, respectively. High voltage stress is subjected to the copper electrode to create a surface discharge on the liquid surface in air and simulate low discharge electrical faults. The high-voltage electrode is a cylindrical shaped (copper) with 15 mm of diameter 10 mm long. Efforts are made to suspend it at the center of the test cell. The electrode is suspended at a height of approximately 1 inch from the liquid surface. This 1 inch is because authors closely resembled the said standard geometry for the setup. After filling of 100 ml liquid in the discharge test cell and suspending the electrode as per the geometry mentioned in the standard, one may notice an air gap of approximately 1 inch. This allows us to generate a fine discharge on the liquid's surface. The change in gassing tendency of the insulating fluids due to discharging activity is performed by the change in pressure that is recorded by a suitable manometer. The change in pressure is recorded every hour. A liquid filled test cell is vacuumed to a pressure less than 1 Torr prior to the application of high voltage. It is noticed that the gassing tendency of synthetic ester is higher than mineral oils. It is known that ester have the tendency to release their own gases. Therefore, to verify this, fresh synthetic ester has been tested for gassing stability without applying high voltage. The corresponding pressure changes are also presented in Figure III-2b). However, the type of generated gases may vary. The information on the type of gases are discussed in the later section of this article.

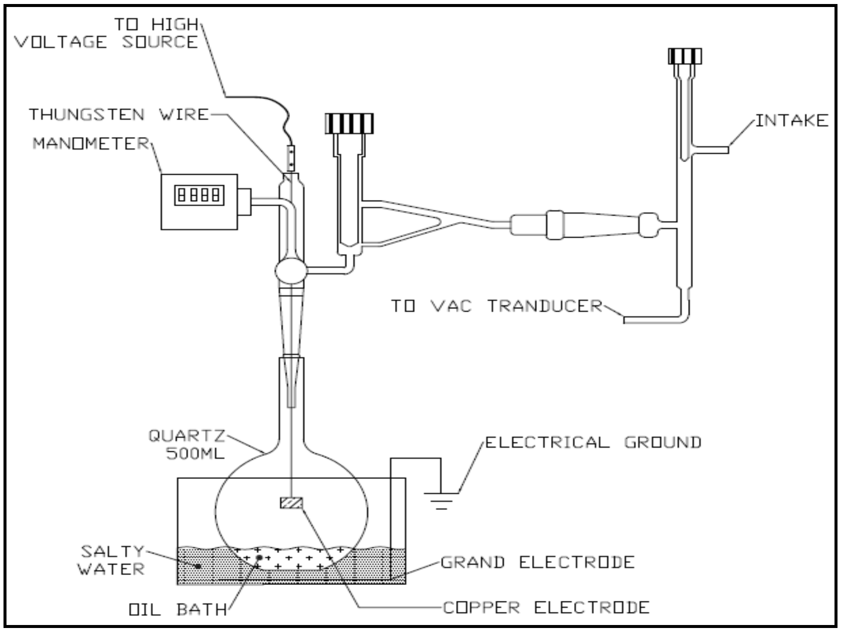
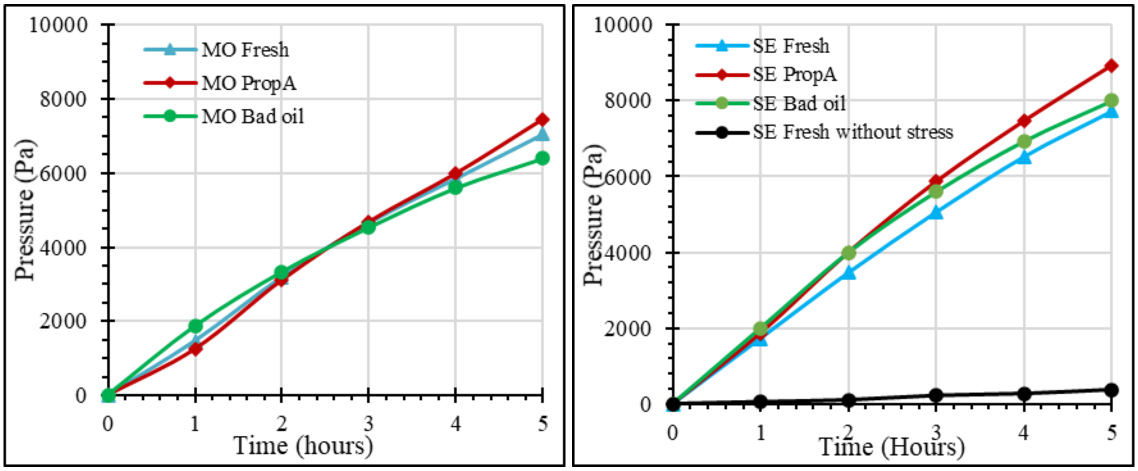


Figure III-1: Illustration of experimental setup to simulate low energy faults.



a) b)

Figure III-2: Illustration of change in pressure with discharge time: a) for mineral oil; b) for synthetic ester.

3.3 RESULTS AND DISCUSSION

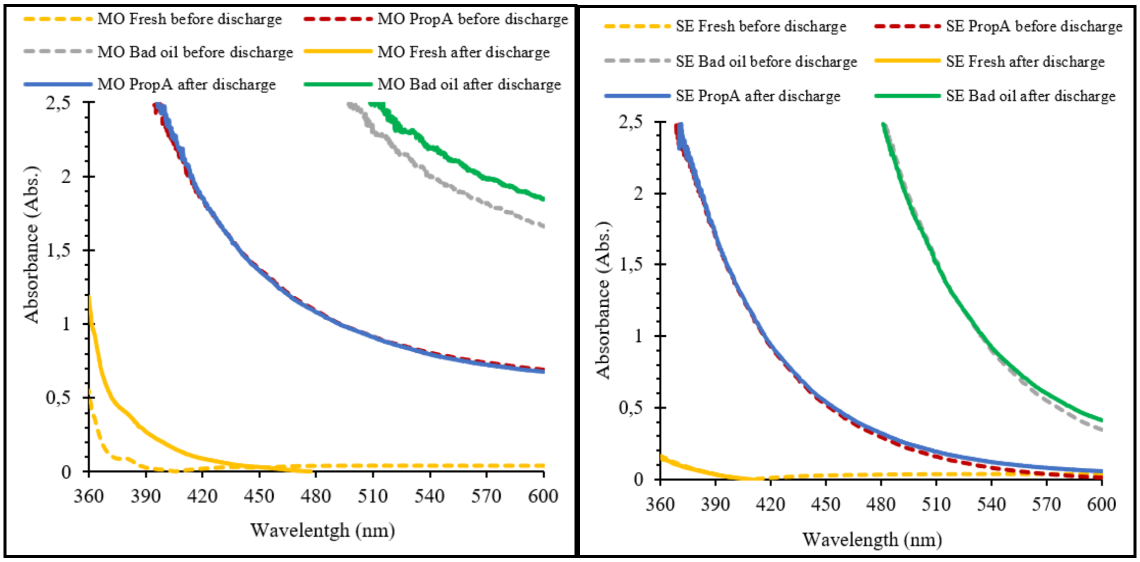
3.3.1 INFLUENCE ON LIQUID DEGRADATION

3.3.1.1 ULTRAVIOLET VISIBLE SPECTROSCOPY (ASTM D 6802)

Ultraviolet visible spectroscopy (UV/Vis) is performed as per ASTM D 6802 to understand the concentration of dissolved decay contents in the insulating fluids. UV/Vis is performed before and after simulating the discharges.

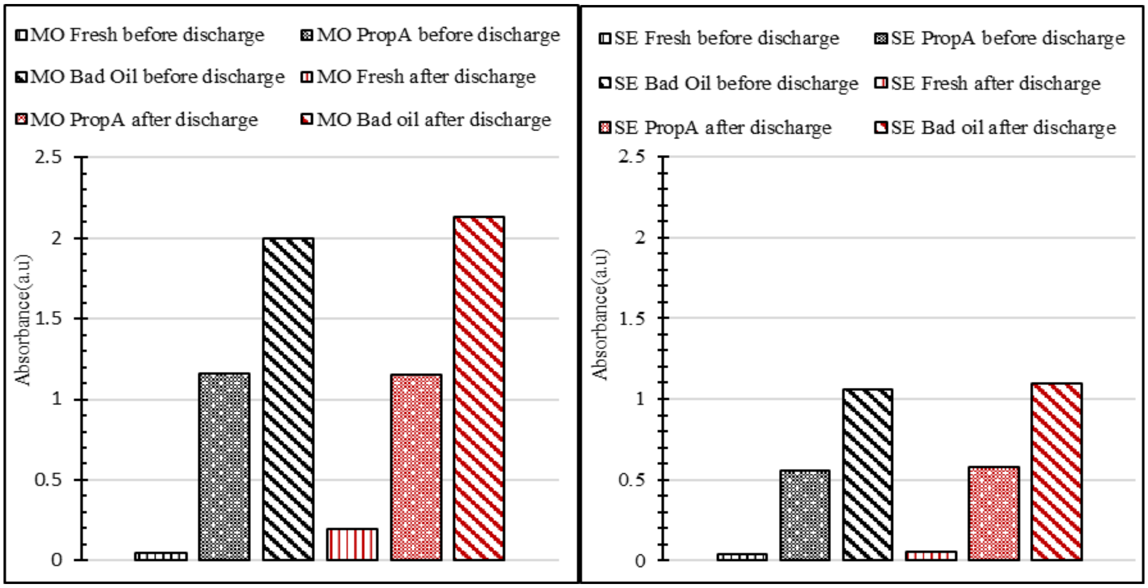
The UV spectral curves of fresh, proposition A class (Prop. A) and bad class before and after low energy discharges for mineral oil and synthetic ester are presented in Figure III-3. The concentration of dissolved decay contents in the liquids is changed due to low energy discharging. This is because of the ionization created by the continuous surface discharges; these discharges will generate free radicles, water, and polar solvents due to the ionization and oxidation process. The distribution of absorption curves is seen proportional to the liquid aging factor. This is because of the increase in liquid absorbance to light with increase in degradation products. It is observed that for both the liquids, for Prof A class, a significant difference is not noticed with low energy discharge. This may be attributable to the manual addition of decay particles. However, an observable difference is seen in case of mineral oil (bad class). The shift of the absorbance curves with low energy electrical faults is seen higher in case of mineral oil as compared to that of the synthetic ester. It may be therefore understood that synthetic ester exhibit a good stability as compared to mineral oils towards the degradation that is caused by corona discharges.

Liquid absorbance and turbidity are reported in this section. The changes in average absorbance at different wave lengths (360–600 nm) for before and after low energy discharges for mineral oil and synthetic ester are presented in Figure III-4. The absorbance of the liquids increased proportionally with thermal degradation. However, a much less change in absorbance is noticed with low energy discharge. The possible increase in dissolved decay contents under electrical faults may be better evaluated under higher discharge times.



a) b)

Figure III-3: Ultraviolet (UV) spectral curves of insulating liquids before and after discharges at different aging conditions: a) for mineral oil; b) for synthetic ester.



a) b)

Figure III-4: Change in absorbance at different aging conditions for before and after discharge: a) for mineral oil; b) for synthetic ester.

3.3.1.2 TURBIDITY (ASTM D 6181)

Turbidity of fresh, proposition A class (Prop. A) and bad class liquids before and after low energy discharges is measured as per ASTM D6181. The variations in the turbidity at different conditions is presented in Figure III-5. The increase in decay particles that are dissolved in the liquid and high molecular weight decay contents affect the ability of the liquid to be transparent to light. As the concentration of these degradation byproducts increase with an increase in thermal aging, the turbidity of the insulating liquid increases. In Figure III-5 and Figure III-6, it is seen that turbidity increases with aging and the trending in the turbidity of the liquids with low energy electrical discharge is seen to be similar for mineral oil and synthetic ester at different aging factors. The turbidity of fresh liquids is increased which is normal.

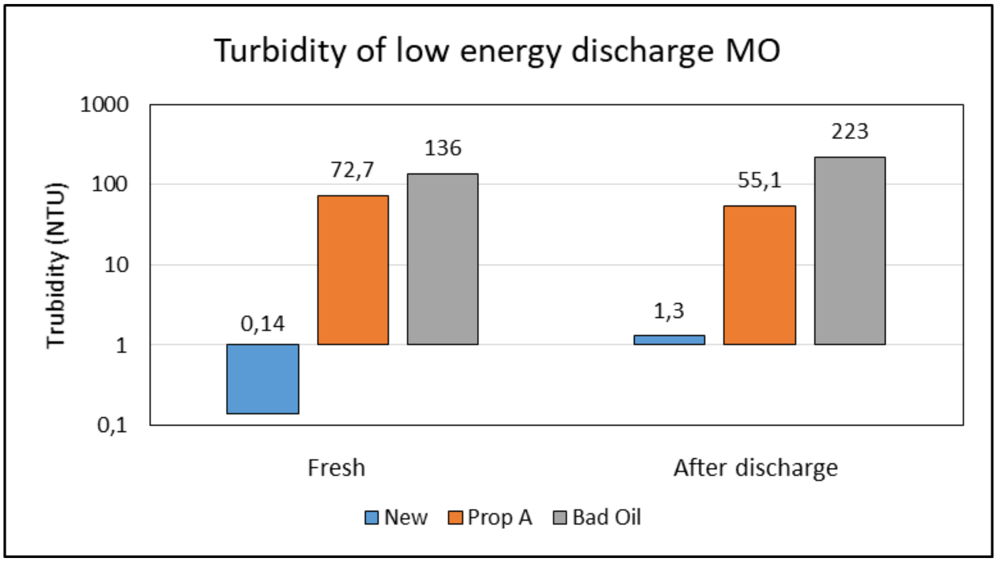


Figure III-5: Change in turbidity of liquids at different aging conditions for before and after discharge for mineral oil.

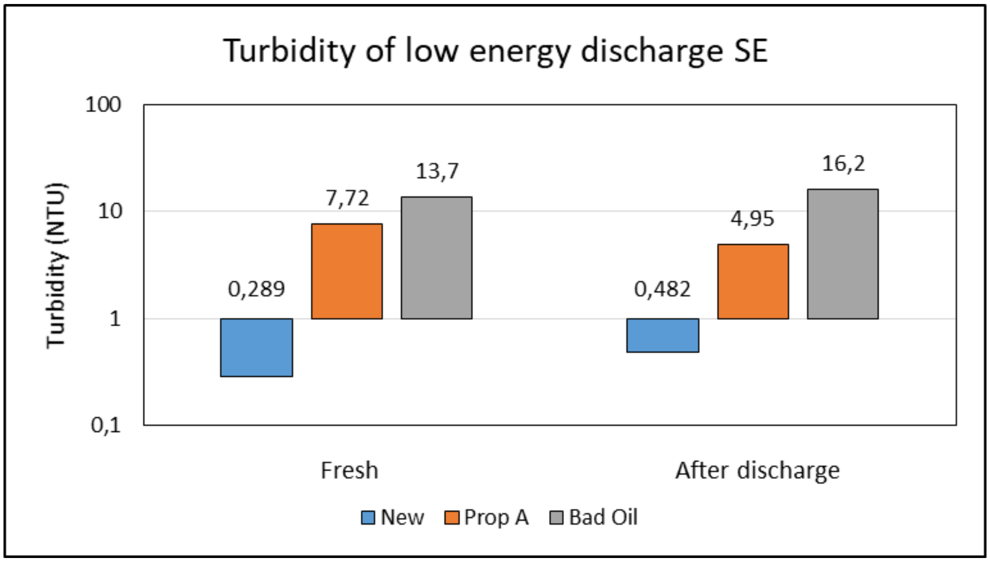
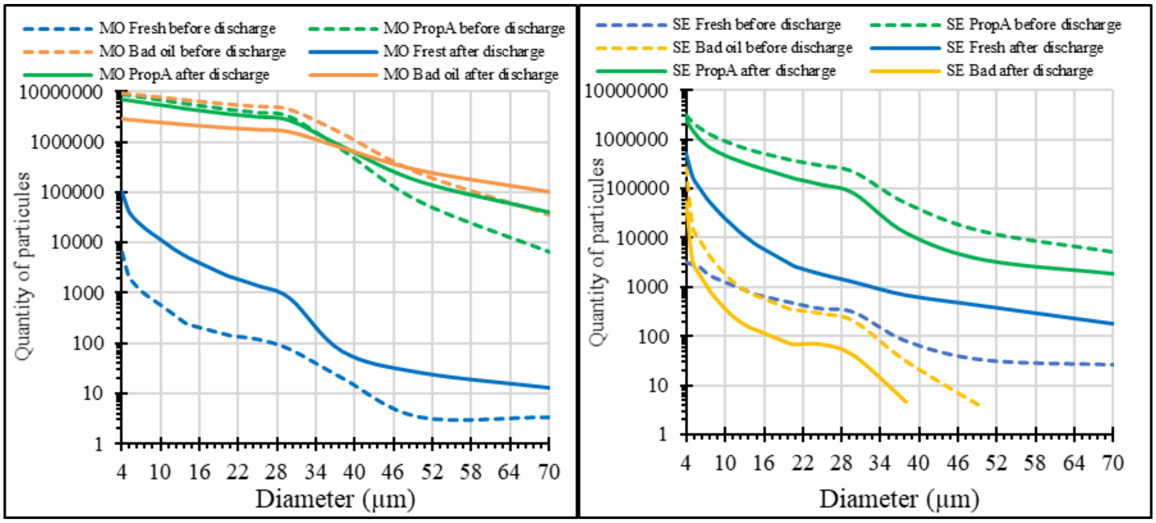


Figure III-6: Change in turbidity of liquids at different aging conditions for before and after discharge for synthetic ester.

Fresh insulating liquid is free from cellulose decay particles and other degradation products. Therefore, free radicles and oxidation products generated due to electrical discharges play a critical role in affecting the liquid quality. Therefore, the turbidity of fresh insulating liquid is seen to be increased for mineral oil and synthetic ester with electrical discharges. However, for Prop. A and bad class liquids, turbidity increased and decreased, respectively, followed by electrical discharges. The concentration cellulose decay particles are more in case of bad oils (manually added while preparing samples) as compared to Prop. A. This concentration allowed for differentiation between different classes. Therefore, it is understood that the presence of high molecular weight decay particles plays a significant role under electrical faults associated with low energy discharges. The scope of crumpling and agglomeration of free radicles and decay particles under the influence of electrical discharge (9 kV) for five hours should also be considered to understand the change in turbidity of the oils.

3.3.1.3 PARTICLE COUNT (ASTM D 6786)

A programmable particle counter equipment has been employed as per ASTM D 6786 to study the number of particles in the mineral oil and synthetic ester. Each measurement is carried out three times and the average value is considered as a final particle count. It should be mentioned that 100 ml sample holder is used with 80 ml of liquid in it for each measurement. The details of particles count for fresh, Prop. A and bad class before and after low energy discharges for mineral oil and synthetic ester are presented in Figure III-7. As expected, the number of particles in the liquid are increased with a simulation of electrical discharge in case of fresh mineral oil and synthetic ester. This increase in particles for fresh liquids is due to ionization and formation of free radicles due to ionization and oxidation reactions. The increase in particles for synthetic ester are slightly more than mineral insulating oils. This process is accompanied by introducing dissolved gases, which is evident with high-pressure changes for synthetic ester in Figure III-1. The analysis on the type of the dissolved gases generated is presented in the next section.



a) b)

Figure III-7: Change in number of particles at different aging conditions for before and after discharges: a) for mineral oil; b) for synthetic ester.

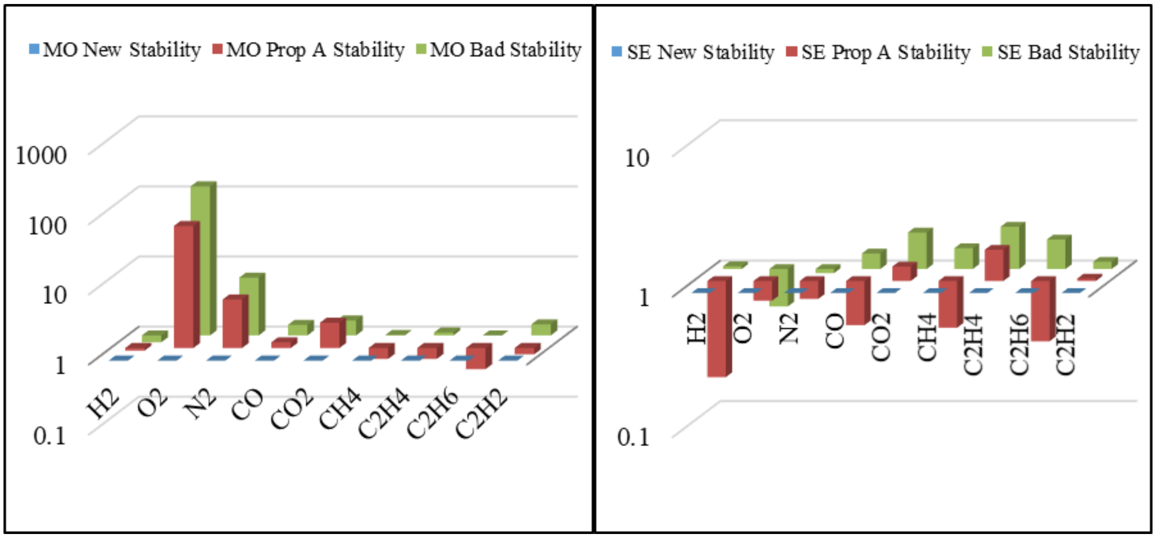
The number of particles in the aged synthetic ester reduced with a simulation of electrical discharge. This may be due to an agglomeration of high molecular weight decay particles, due to continues and uniform electrical discharge. Particle count results are highly influenced by the agglomeration and breaking of decay particles. The decay concentration remains in the liquid that affects other parameters of the liquid. The results presented in UV spectrum section are in support of this explanation; one may see an increase in the absorbance (aged liquids) and dissolved decay content with existence of faults. Even though the concentration of larger diameter particles is more in synthetic esters, the total number of particles is much lower than that of the mineral oils. As discussed, this is due to the manual addition of sludge. Moreover, the degradation of the cellulose insulants will not be uniform across the cellulose surface and hence contributing to different decay particles.

3.3.2 DISSOLVED GAS ANALYSIS

The gassing tendency of an insulating liquid is defined as the chemical decomposition of certain vulnerable hydrocarbons under the impact of electrical stresses [136] [137]. In the present work, after five hours of continues electrical discharge at 9 kV, a liquid sample of 30 ml is sampled with a syringe from the discharge test cell. The 30 ml of liquid sample has been subjected to dissolved gas analysis to understand the gases generated due to low energy discharges. The absolute values are presented in Table III-2 and to report the changes clearly, per unit (p.u.) values of the change in dissolved gases with discharge are plotted in Figure III-8. Absolute values of the fresh liquids are taken as reference for quick comparison.

Table III-2: Absolute values of the dissolved gases in ppm.

	MO Fresh	MO Prop. A	MO Bad	SE Fresh	SE Prop. A	SE Bad
Hydrogen	1910	1755	1527	1330	275	1390
Acetylene	16	13	23	24	25	27
Ethane	100	50	100	145	54	235
Ethylene	10	7	11	3	5	6
Methane	1004	701	1018	1080	502	1520
Carbon Monoxide	459	553	649	992	481	1280
Carbon Dioxide	4114	9445	6724	8840	11200	16100
Nitrogen	13782	67924	91947	55100	41100	51500
Oxygen	100	5500	13358	19200	13900	10400



a) b)

Figure III-8: Change in generation of dissolved gases (p.u.) at different aging factors with low energy discharge (stability): a) For mineral oil; b) for synthetic ester.

In order to have a proper interpretation of the changes, it was decided to plot p.u. values on a logarithmic scale. For mineral oil, there is a huge increase in O_2 with aging. The quantity in ppm of O_2 is increasing 134 times from a new to bad class liquid under the influence of low energy electric faults. There is also an increase in N_2 of almost seven times. The changes in other gases go from 0.8 to fewer than two times. According to Henry's law, the amount of gases dissolved in mineral oil are dependent on the partial pressure of existing gases above the surface. The degree of degradation of the liquid submitted to low energy discharge is not affecting as much the high energy discharges. The gassing tendency of mineral oil is noticed to be much lower than that of synthetic ester. There is a direct relation between the aromatic molecules and the gas absorbing effect [129]. The increase of oxygen is mainly due to breakage of chemical bonds associated with mineral insulating oil [39]. The trending of the fault gases with aging factors as per the Duval triangle and Duval pentagon methods is presented from Figure III-9 to Figure III-12. The nature of fault types is noticed to be similar for both SE and MO but with different intensities. For both SE (non-mineral oil Duval triangle 3) and MO (Duval triangle 1), the faults are identified at the border of PD-T1 and DT [138]. Fault gas analysis from the Duval Pentagon method for synthetic ester is indicated D T1 for fresh and S for Prop A and bas class. For the bad class, D2 (high energy discharge fault) fault condition is obtained. This is because of the high concentration of conducting particles in the fluid of bad class that allowed more intensity of discharge [139]. Duval pentagon for mineral oil revealed S (Stray gassing of liquid at 120 °C and 200 °C) for all class respectively [100].

The difference in gassing tendency is noticed at different aging factors, which allowed the reveal for the fault gassing behavior with aging times. The aging factors are chosen based on the acidity values. This facilitated us to understand the relation between aging marker and gassing tendency of insulating liquid. As the mineral oil and synthetic ester are aging, a difference on the values of the diagnostic gases and fault analysis results were highlighted for low energy discharges. This simulates the corona discharging activity at different operating times. According to the different diagnostic tools with those including Duval triangle and Duval pentagon, an interesting trending is especially noticed with generations of fault gases and fault types. The following figures are the updated ones and some of the below are different from those that are published in the literature by the author of this thesis.

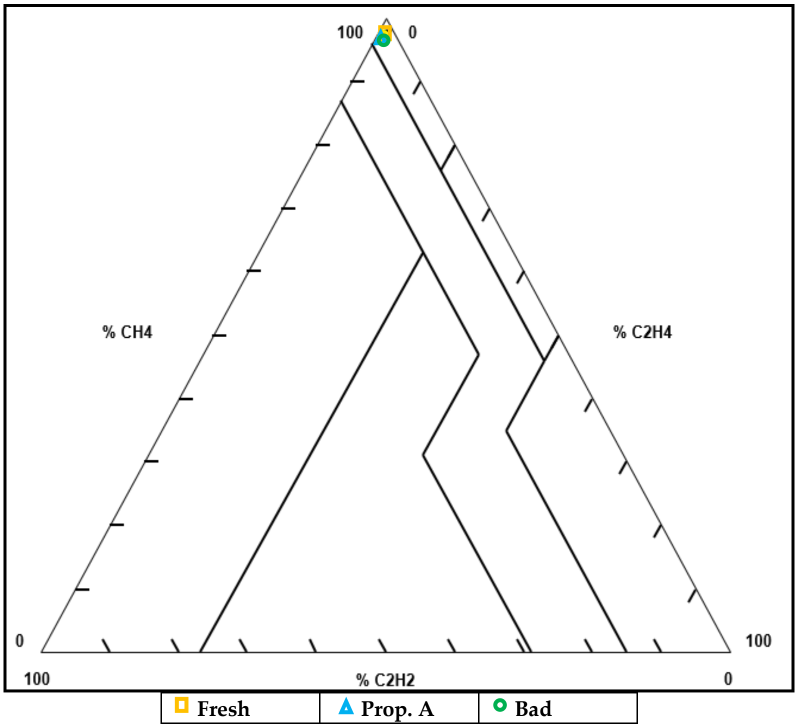


Figure III-9: Representation of fault gases in Duval triangle for Mineral oil.

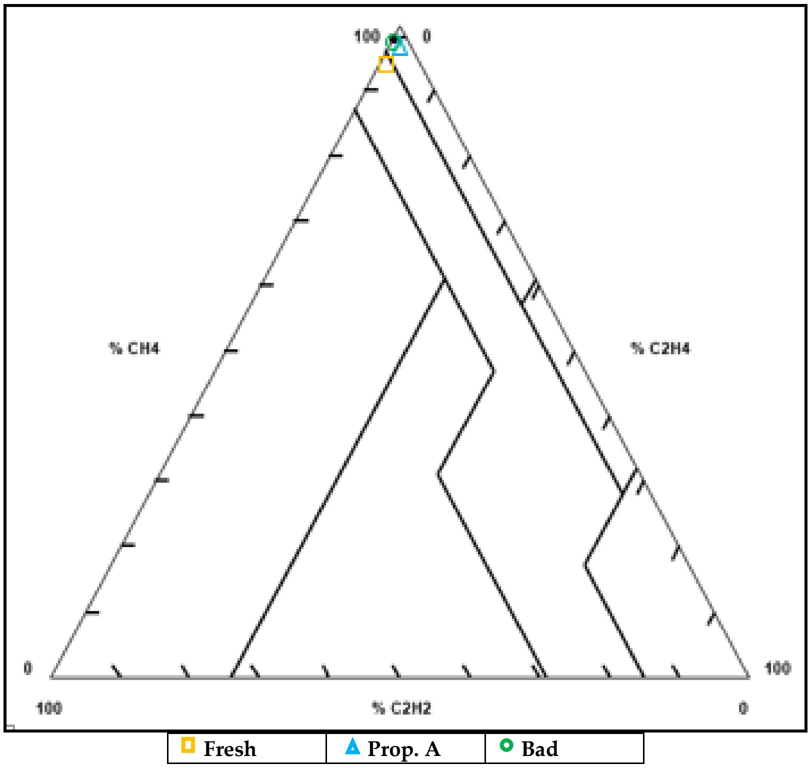


Figure III-10: Representation of fault gases in Duval triangle for synthetic ester.

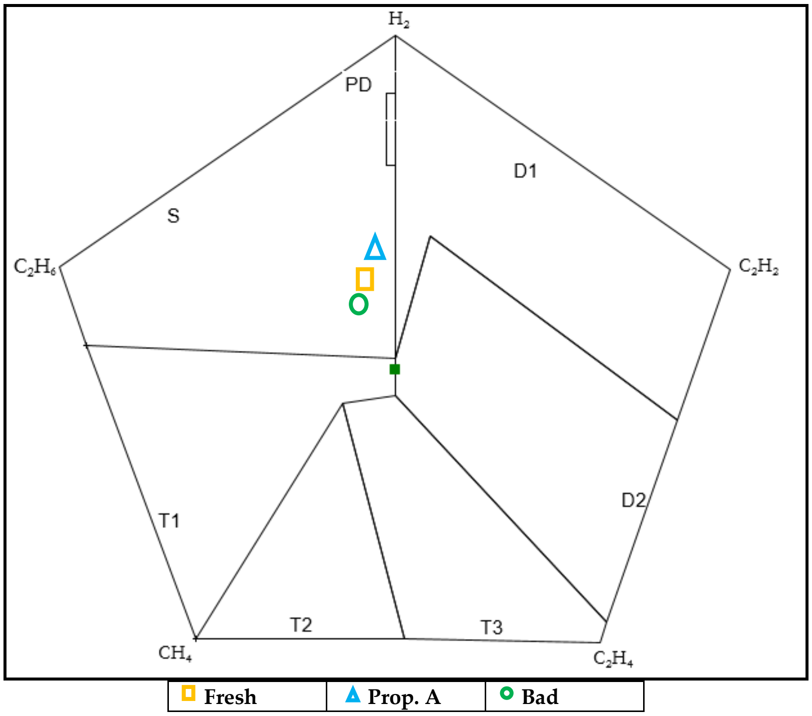


Figure III-11: Representation of fault gases in Duval pentagon for mineral oil.

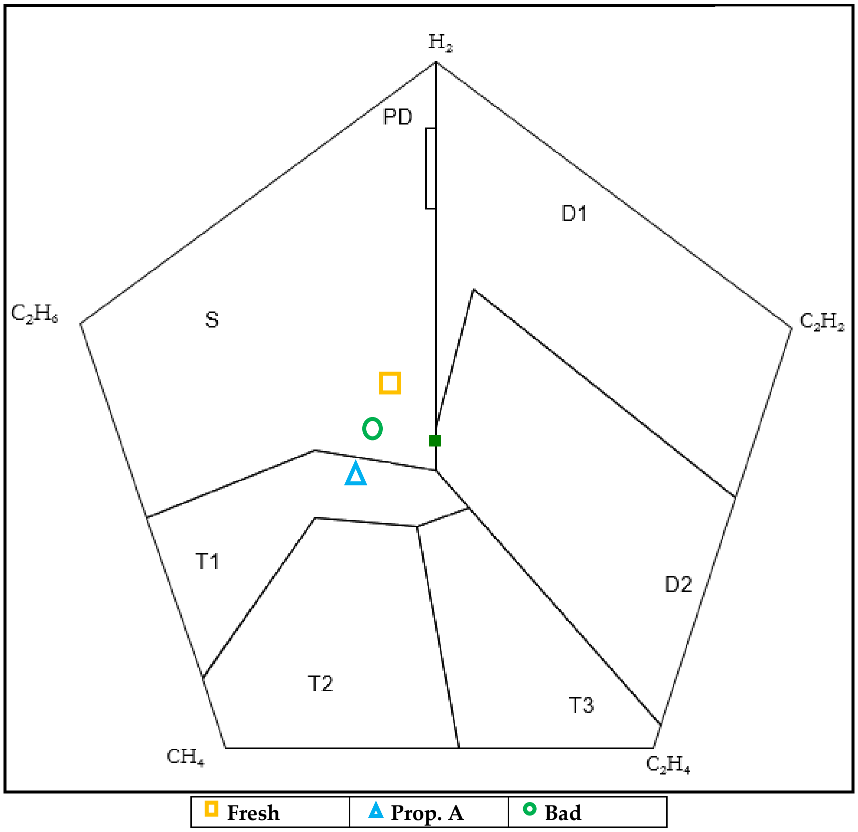


Figure III-12: Representation of fault gases in Duval pentagon for synthetic ester.

For low energy discharge, the fault diagnosis in the triangle witnessed a propagation from partial discharges to combine thermal and electrical faults with increase in the aging. In the case of synthetic ester, only partial discharges have been witnessed at different aging factors. Fault diagnosis with the pentagon method revealed the mineral oil involved in stray gassing and partial discharging activity with aging. Similarly, synthetic ester are observed to be involved in stray gassing and thermal fault. However, further analysis of dissolved gases and fault diagnosis is required to further comment on the trending of fault gases. One can better understand the gassing tendency under low energy discharges if a comparative gassing behavior is simulated for thermal faults under similar aging conditions.

3.4 CONCLUSION

The behavior of mineral oil and synthetic ester at different aging factors under low energy discharges are investigated. The influence of corona discharges (including sparking) on the degradation and gassing tendency at different aging factors has been reported. Liquid degradation is analyzed by turbidity, concentration of dissolved decay products, and particle count. The influence of low energy electric discharge faults on liquid degradation at different aging conditions is found to be better in case of synthetic ester liquids. Dissolved gas analysis and corresponding fault diagnosis is performed by adopting Duval triangle and pentagon methods for mineral oil and non-mineral oils (synthetic ester). Considering the influence of degradation and gassing behavior, one may assume that the existence of electrical faults will involve a generation of excess high molecular weight products as compared to low molecular weight products. Further, depending on the degree of fault intensity, the phenomena of agglomeration or splitting of decay particles may be noticed. Under the influence of low energy discharges, the fault gases in mineral oil are involved with combined electrical and low temperature thermal faults accompanied by stray gassing whereas only partial discharges (discharge of low energy including sparking and high energy) are diagnosed in case of synthetic ester. It is to be understood that the apparatus simulate the fault and does not represents the entire phenomenons that happens in the fluid. The propagation of fault conditions with aging is noticed to be higher in case of mineral oils as compared to synthetic ester.

Chapter IV

INFLUENCE OF AGING ON OIL DEGRTADATION AND GASSING TENDENCY UNDER HIGH ENERGY ELECTRICAL FAULTS FOR MINERAL OIL AND SYNTHETIC ESTER

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INFLUENCE OF AGING ON OIL DEGRTADATION AND GASSING TENDENCY UNDER HIGH ENERGY ELECTRICAL FAULTS FOR MUNERAL OIL AND SYNTHETIC ESTER

Résumé

Dans ce travail, l'huile minérale et l’ester synthétique ont été sélectionnés à différents facteurs de vieillissement (basés sur les valeurs d'acidité). Les huiles fraîches et vieillies ont été soumises à des décharges d'énergie élevée (100 claquages répétés) pour simuler des défauts électriques d'intensité très élevée. Le but de ce travail est de comprendre l'influence des défauts électriques à haute énergie sur la dégradation de l'huile et la tendance au gazage dans différentes conditions de vieillissement. Dans le présent article, l'influence des décharges à haute énergie sur la dégradation et la tendance au gazage à différents facteurs de vieillissement est rapportée pour l'huile minérale et l’ester synthétique. La dégradation de l'huile est décrite en adoptant la spectroscopie UV, la turbidité et le compteur de particules conformément aux méthodes d'essai standard ASTM. L'analyse des tendances de gazage et des défauts de gaz est comprise par l'analyse des gaz dissous utilisant les méthodes du triangle de Duval et du pentagone de Duval pour les huiles minérales et les huiles non minérales. Il est à noter que les résultats de l'appareil simulant le défaut dans les liquides ne proviennent pas d'un véritable transformateur et d'après les résultats, il est constaté que l'influence des décharges à haute énergie sur la dégradation de l'huile est plus élevée dans l’huile minérale que dans l’ester synthétique. L'intensité de la tendance aux gaz est plus élevée pour le fluide ester, cependant, selon les méthodes de Duval, les conditions défectueuses sont à des niveaux inférieurs par rapport aux huiles minérales.

Abstract

In this work, mineral oil and synthetic ester were selected at different aging factors (based on acidity values). Fresh and aged oils have been subjected to high energy discharges (repeated 100 breakdowns) to simulate electric faults of highly vulnerable intensity. The intent of this work is to understand the influence of high energy electric faults on oil degradation and gassing tendency at different aging conditions. In the present paper, the influence of the high-energy discharges on degradation and gassing tendency at different aging factors is reported for mineral oil and synthetic ester. Oil degradation is reported by adopting UV spectroscopy, turbidity, and particles counter as per ASTM standard test methods. Gassing tendencies and faults gas analysis are understood by dissolved gas analysis using Duval triangle and Duval pentagon methods for mineral oil and non-mineral oils. It should be noted that the results from the apparatus simulating the fault in liquids do not come from a real transformer unit and according to the results it is found that the influence of high energy discharges on oil degradation is higher in mineral oil to that of the synthetic ester. The intensity of gassing tendency is higher for ester fluid; however, as per the Duval methods, the faulty conditions are at lower levels as compared to mineral oil.

4.1 INTRODUCTION

Insulation degradation in oil-filled transformers is one of the main concerns for condition monitoring engineers. It is known that the transformer failure rate and service life are mostly governed by the insulation system [34]. There are several factors responsible for insulation deterioration, out of which, the heat liberated from core-winding assembly and electrical discharges play a vital role [140]. It is known that electrical stress and thermal stress expedite the degradation rate of oil-paper insulation. Subsequently, this early degradation leads to failure of the insulation system and hence premature aging of the transformer. Thus, careful monitoring of the degradation rate and appropriate condition monitoring actions are essential for the successful operation of the transformers. This allows the utility and engineers to meet the designed life while leading to efficient asset management [141] [142].

The influence of aging on oil/paper insulation deterioration is generally understood by simulating an accelerated aging factor which expedites the deterioration rate. This accelerated aging factor is generally achieved by either thermal or electrical stressing in the laboratory environment. To date, various researchers reported the influence of aging on oil degradation parameters for mineral insulating oils [143]. Meanwhile, in understanding the behaviour of alternative insulating fluids, several authors reported the degradation behaviour of synthetic ester vis-à-vis mineral insulating oils [87] [64] [67]. It is found that the degradation aspects of synthetic ester are better than that of the mineral insulating oils. Importantly, numerous researchers are affirmative towards accepting synthetic ester as a potential alternative for transformer insulation.

Meanwhile, any sudden electrical discharges and thermal hotspots may influence the oil properties and involve in generating different fault gases. This influence on properties and gassing tendency of the oils is highly attributed to the deterioration level and type of the insulants (oil and paper). In other words, the effect of electrical discharges and hotspots will not be the same for mineral oil or ester fluids at different aging conditions. Also, the degree of impact will be dependent on the energy of discharge (high and low), duration of discharge, and temperature of the hotspot. High-energy discharges are mainly due to arcing caused by short-circuit faults and winding deformations. These discharges involve excessive generation of hydrogen and acetylene with traces of methane and ethylene. If this fault occurs in cellulose insulants, carbon monoxide and carbon dioxide will also be traced. High energy discharges are detrimental to the insulation system [135]. High-energy discharges are also associated with high temperatures that may cause premature thermal degradation of oil/paper insulation. Low energy discharges are mainly due to partial discharges and minor dielectric defects, and these low energy discharges will involve in the generation of hydrogen, methane, ethane, and ethylene while deteriorating oil/paper insulation [135]. If partial discharges occur within the cellulose insulants, carbon monoxide and carbon dioxide will also be noticed. Hotspots are aroused from severe local overheating caused by loading cycles and internal faults. The sudden temperature raised due to hotspots leads to the formation of gas bubbles along with the deterioration of the oil/paper insulation [54]. Hence, there is a need to understand the influence of high-energy discharges and low energy discharges separately at different aging conditions for mineral oil and synthetic ester.

The intent of this research is to understand the influence of the high-energy discharge and low energy discharge on the degradation level of oil and gassing tendency at different aging factors. Hence, high-energy discharge and low energy discharge faults in mineral oil and synthetic ester have been created under laboratory conditions as follows:

i) High-energy discharge: repeated breakdowns (100 times) of the oil by using disk electrodes at a 2.5 mm gap with two minutes of the gap between every breakdown.

ii) Low energy discharge: continues discharge of 9 kV on the surface of the oils for five hours by using a suitable laboratory model. The results of this study were recently reported by authors group in [144].

Interfacial tension (IFT) and acidity are the widely accepted aging markers to monitor the degree of insulating fluid deterioration [145]. Peroxides are primary oxidation compounds in insulating liquids and all secondary oxidation compounds (volatile, non-volatile, high molecular weight, and free fatty acid) derive from hydro-peroxide decomposition [146]. Testing techniques used to monitor the level of peroxide in oxidised oil samples include titration, chemiluminescence, electron spin-resonance spectroscopy, ultraviolet (UV) spectroscopy and infrared spectroscopy [146]. Before colloids appear, the first sign will be the drop of the in the IFT followed by an increase of the total acid number (TAN). Both test methods depict clear correlation. Due to the higher polarity of ester liquids in comparison to mineral oils, the IFT test gives no meaningful information, presenting low to no variation along with fluid degradation [147]. Therefore, acidity is adopted as an aging marker for understanding the level of oil degradation. It is to be recalled that there is a direct relationship between acidity, turbidity, and UV absorbance [28]. Therefore, one may monitor the degree of aging by turbidity, UV spectral curves, and oil absorbance information presented before high energy discharge in section 4.3.

In this paper, the results of a study of the influence of high energy discharge electric faults on the oil degradation and gassing tendency of MO and SEs for fresh and aged oils are reported. Ageing conditions include Proposition A (Prop. A) class (moderately aged oils) and bad class oils (highly aged oils), which are ensured by acidity measurements [131]. Mineral oil and synthetic ester of unused, Proposition A class, and Bad class are subjected to repeated high energy discharges. To understand oil degradation, dissolved decay products (DDP), absorbance, turbidity, and particle counter measurements are performed as per ASTM standards. These measurements are performed before and after the discharge simulations. Later, dissolved gas analysis is performed using Duval triangle and Duval pentagon methods on the oils after repeated high energy discharge to understand the tendency of gassing at various aging conditions.

4.2 EXPERIMENTAL SET-UP

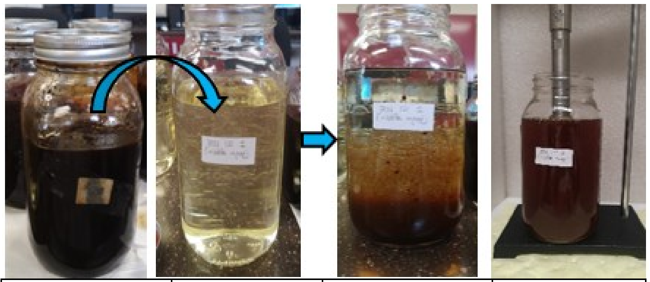
4.2.1 OILS AND TEST SAMPLE PREPARATION

The properties of mineral oil and synthetic ester adopted for the present study are presented in Table IV-1. Initially, fresh mineral oil and synthetic ester are subjected to accelerate thermal aging as per modified ASTM D1934 standard at 115ºC with copper (3g/l) catalyst and cellulose (1:20) in the presence of oxygen. For excessive degradation of the base oils, a large proportion of cellulose kraft papers (1:20) are used. Later after 2000 hours of degradation, highly degraded and crushed oil/paper insulation is subjected to sonication for 30 seconds using Qsonica Q1375 Sonicator. This less sonication time is selected to allow protecting the existing oil chemical properties [39].

Table IV-1: Significant properties of the base oils

Parameters	MO	SE
Power Factor 50 Hz 90 °C, IEC 60247	<0.001	<0.008
Breakdown Voltage (kV) IEC 60156	>70	>75
Water content (ppm) IEC 60814	<20	50
Acidity, IEC 62021	<0.01	<0.03
Density at 20˚C (kg/dm^3)	0.869	0.97
Viscosity (cSt @ 40 °C) ISO 3104	9.2	29
Fire point (°C) ISO 2592	-	316
Flash point (°C) ISO 2719	148	260
Pour Point (°C) ISO 3016	-54	-56

This sonication helped to make further a fine solution of degraded oil and paper, which is normally treated as sludge and decay content. Later, this decay content is transferred to fresh oil at the appropriate proportions to reach the desired levels of neutralization number. Finally, the solution of fresh oil and sludge are again subjected to 30 seconds of sonication followed by five minutes of magnetic stirring to ensure gentle mixing of the test samples. The process of test sample preparation is presented in Figure IV-1.



Crush of highly aged oil/paper

Fresh oil

Blend of sludge and fresh oil

Sonication of sample

Figure IV-1: Illustration of sample preparation.

Fresh and unused oils are used to prepare Proposition A (Prop. A) class and Bad class oils based on neutralization numbers. Later, mineral oil and synthetic ester of fresh, Prop. A, and Bad oils are used for the present experimental studies. The details of the oil classifications are presented in Table IV-2, Table IV-3 and Figure IV-2 highlights the details of the acidity measurements performed to ensure Proposition A (Prop. A) and Bad oils classes for mineral oil (MO) and synthetic ester (SE).

Table IV-2: Oil classification and acidity values as per [54]

Type	Oil classifications	NN
1	Good Oils	0.0 – 0.10
2	Proposition A Oils	0.05 – 0.10
4	Bad Oils	0.16 – 0.40

Table IV-3*: *Oil classification and acidity values

Sample	Acidity test 1 mg KOH/g	Acidity test 2 mg KOH/g	Average	Std. deviation	Class
MO 1	0.0818	0.082	0.0819	0.0001	Prop. A
MO 2	0.2757	0.2675	0.2716	0.0058	Bad Oil
SE 1	0.1034	0.092	0.0977	0.0081	Prop. A
SE 2	0.2314	0.2573	0.24435	0.0183	Bad Oil

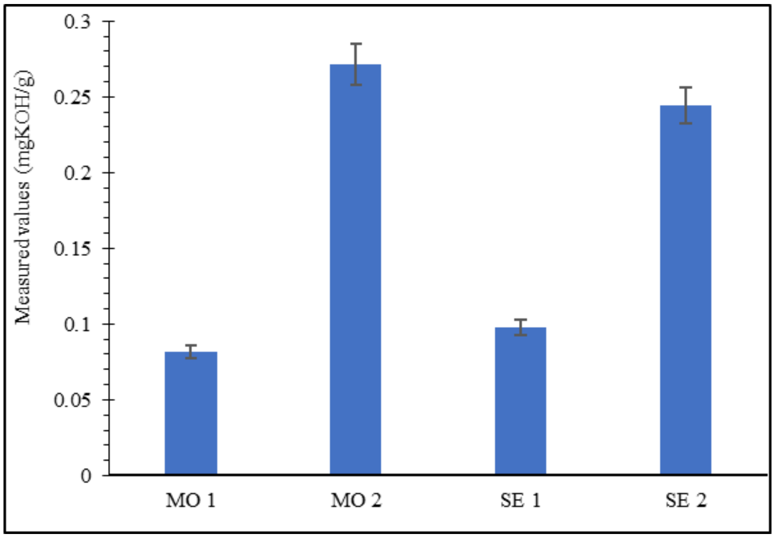


Figure IV-2: Acidity of the oil samples at different oil classes.

4.2.2 HIGH ENERGY DISCHARGE ELECTRICAL FAULTS

Most of the high-energy discharge faults in a transformer occur in the windings due to turn-to-turn insulation breakdown. This may be due to the dielectric breakdown of the insulation between the turns of the winding. Normally, insulation breakdown occurs due to sudden and high magnitudes of current or voltage, which are higher than the expected or rated values. This breakdown of the insulation results in the flashovers of the winding turns and cause short circuits within the winding assembly. These consequences will lead to a severe impact on the insulation system if the fault persists for a long time. This type of faults are witnessed with a significant influence on the integrity of the solid and liquid insulants within the transformer [148]. These faults lead to the generation of contaminants such as water, sediments, and conducting particles, which reduce the dielectric strength of insulating oil. The intensity of the high-energy electrical discharge sometimes turns to continuous arcing that produce a high instant temperature that further degrades the insulation system. These factors cause a pronounced generation of acetylene gas within the oil [148]. According to key gas method of dissolved gas analysis, the quantity of hydrogen and acetylene are reported to be increased with continuous arcing in the insulation system [135]. Hydrogen will be evolved from cellulose insulants along with traces of carbon dioxide and carbon monoxide, if the fault is involved with cellulose insulants.

In the present study, to ensure continuity in the fault, a hundred breakdowns have been created in the laboratory environment as per ASTM D 877 [149] with 2 minutes gap between every single breakdown. To understand the impact of high-energy electrical discharge faults, oil degradation and dissolved gas analysis have been reported. The series of breakdowns on mineral oil is shown in Figure IV-3 and synthetic ester in figure IV-4 for fresh and aged oils.

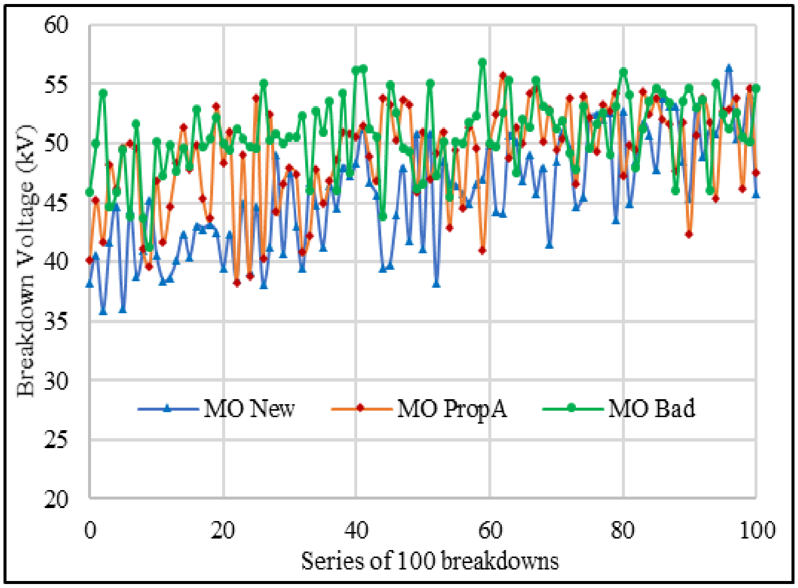


Figure IV-3: Illustration of breakdown voltage values of fresh and aged mineral oil.

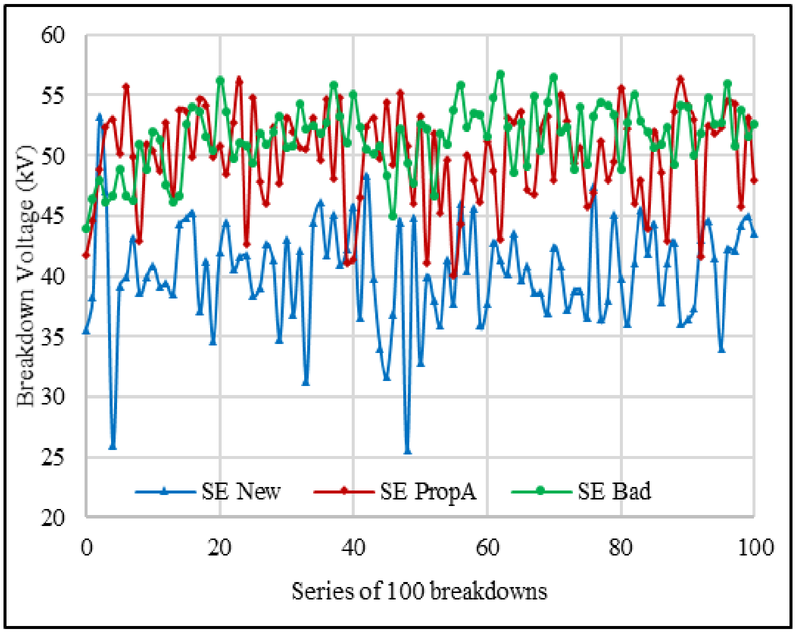


Figure IV-4: Illustration of breakdown voltage values of fresh and aged oils for synthetic ester.

It is to be mentioned that water saturation limit of an insulating liquid increases with aging [150]. Since breakdown voltage is relative moisture content dependant [151], at a given absolute moisture content, the breakdown voltage of the aged oil will be higher than the unused one. Under AC stress, a field-induced drift of particles, located in high field regions, can be entailed by a stress relieve leading to an improvement of the electrical strength, compared to technically clean oil [152]. Since every breakdown causes definite aging/degradation of the insulating liquid, this will lead to an increase in the water saturation limit. This is the reason for the increase in the breakdown voltage of oils with elapsing breakdown times and aging. A statistical analysis conducted by the CIGRE Working Group 12.17 on the root causes of twenty-two transformers and forty bushings (765 kV) failures pointed out that attention must be paid to the source and hazard of particles for 400 kV transformers and above [39].

4.3 RESULTS AND DISCUSSIONS

4.3.1 INFLUENCE ON OIL DEGRADATION

4.3.1.1 ULTRAVIOLET VISIBLE SPECTROSCOPY (ASTM D 6802)

Ultraviolet visible spectroscopy (UV/Vis) provides an assessment of the concentration of dissolved decay products (DDP) in the aged oil. It is established that the quantity of dissolved decay products increases with an increase in the age of oil/paper insulation. This is because the absorbance of the oil to UV and visible rays increases with the increase in the concentration of DDP in the oil.

Thus, the absorbance curves shift to higher wavelengths. The UV spectral curves of fresh, Proposition A class, and Bad class before and after high energy discharge for mineral oil and synthetic ester are presented in Figure IV-5 and Figure IV-6.

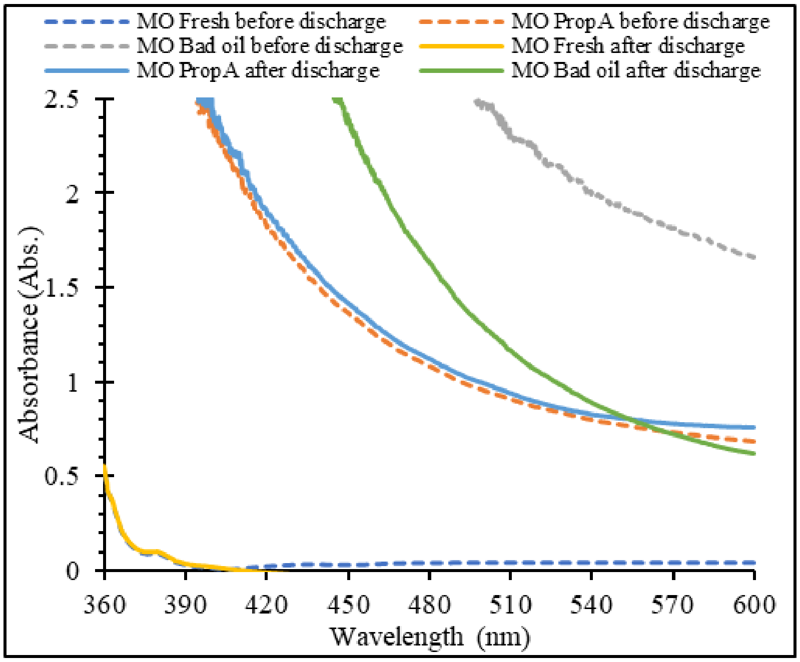


Figure IV-5: UV spectral curves of oils before and after discharges at different aging conditions for mineral oil.

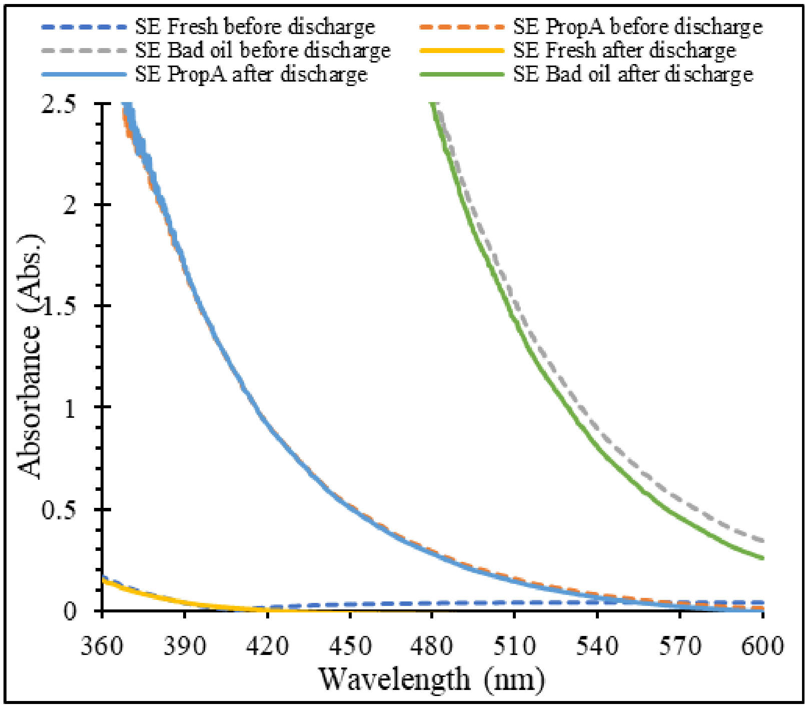


Figure IV-6: UV spectral curves of oils before and after discharges at different aging conditions for synthetic ester.

It is seen that the concentration of decay content in oils is changed due to high energy discharge. This is because of the ionization created by the repeated breakdowns. This repeated breakdown in oil will also allow generating free radicles and oxidizing products that deteriorated the insulating oil. It is to be noticed that the shift in spectral curves is significantly low in the case of synthetic ester. This demonstrates the chemical stability of the synthetic ester towards high-energy discharge electrical faults. It is also seen that Prop. A class with mineral oil is noticed with a very small deviation. This will not indicate the potential of middle-aged mineral oils to resist electrical faults. Rather, this may be due to the non-uniform distribution of cellulose particles within the oil samples. To further understand this, absorbance values of mineral oils and synthetic ester fluids are presented in Figure IV-7 and in Figure IV-8.

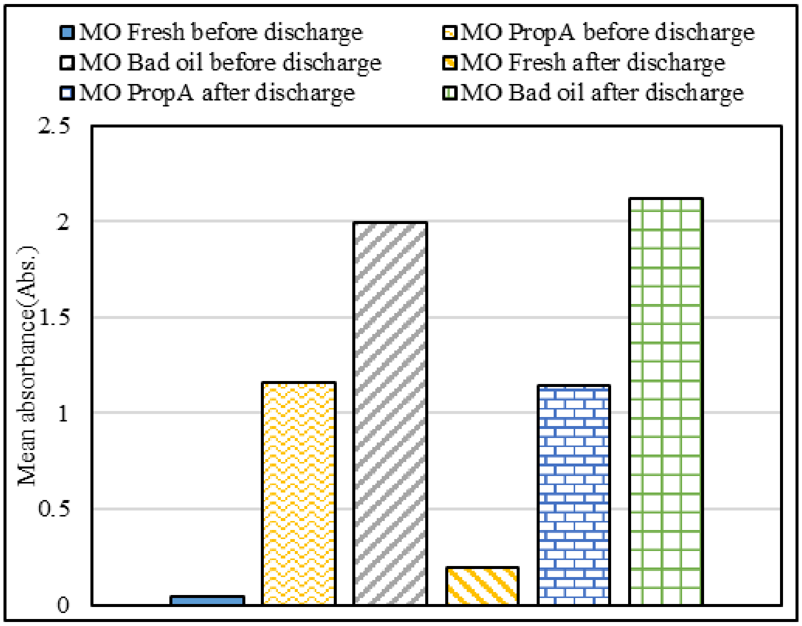


Figure IV-7: Change in absorbance of mineral oil at different aging conditions for before and after discharge.

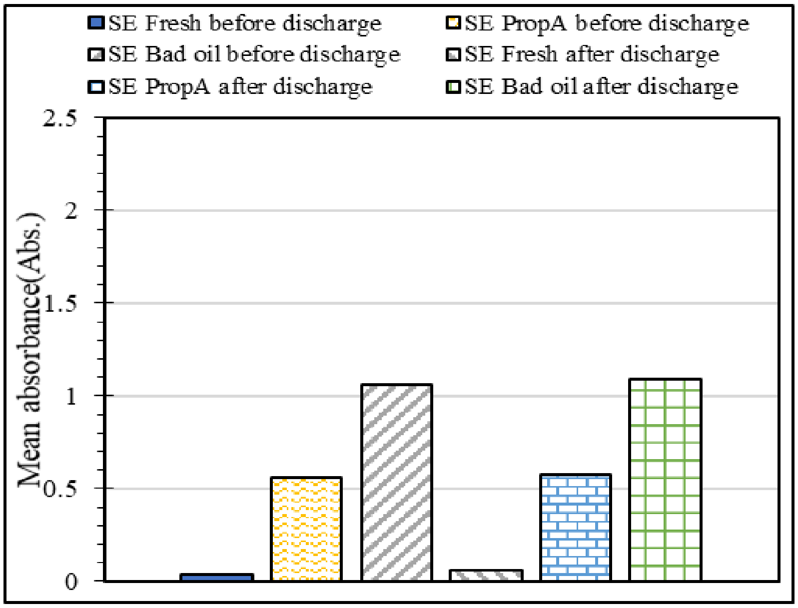


Figure IV-8: Change in absorbance of synthetic ester at different aging conditions for before and after discharge.

The change in absorbance of oils with aging and with high-energy electrical faults is seen in Figure IV-7 and Figure IV-8. As expected, the absorbance of oils is increasing with the increase in age. However, this change is significantly less in the case of synthetic ester.

4.3.1.2 TURBIDITY (ASTM D 6181)

Turbidity of a liquid reveals the ability of the liquid to be transparent. Turbidity is defined as the extent to which the liquid lost its ability to be transparent to light. For transformer oils, turbidity is an important parameter to understand the degree to which oil is degraded. Owing to the decay particles introduced with aging reactions, turbidity of transformer oil increases with aging. In the present work, turbidity of fresh, proposition A class (Prop A), and bad class before and after high energy discharge for mineral oil and synthetic ester are presented in Figure IV-9 and Figure IV-10

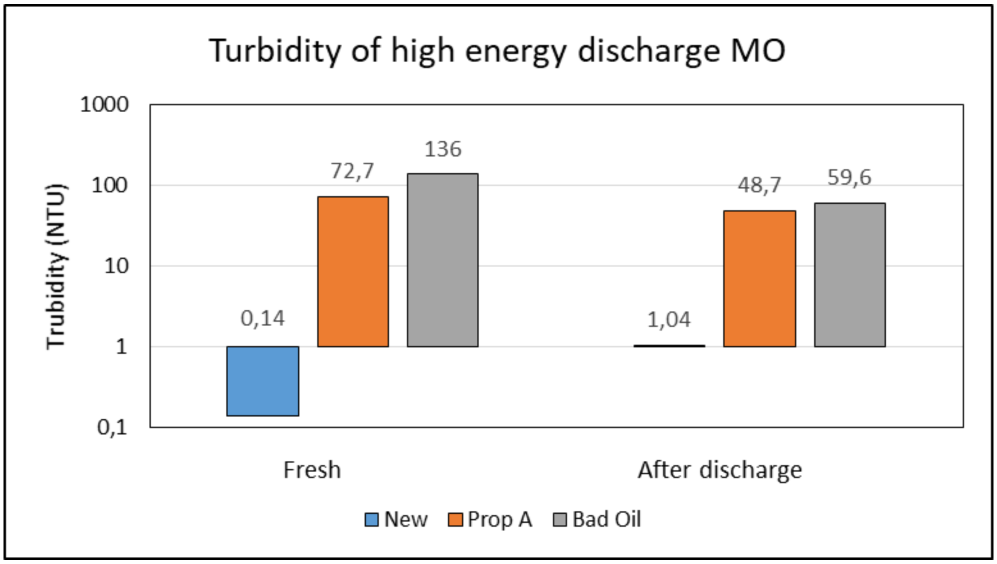


Figure IV-9: Change in turbidity of mineral oil at different aging conditions for before and after discharges.

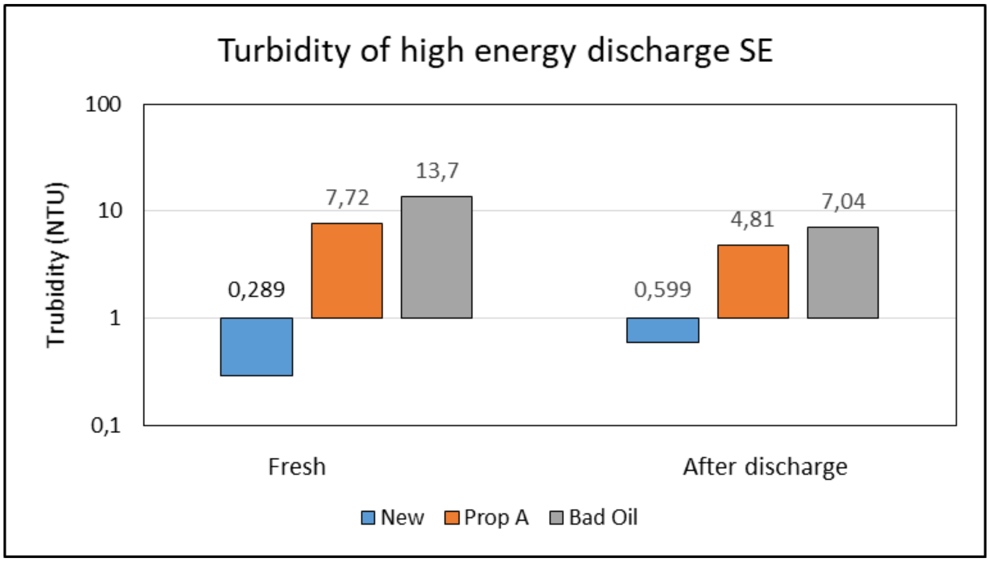


Figure IV-10: Change in turbidity of synthetic ester at different aging conditions for before and after discharges.

As expected, the turbidity of the fresh oil increases with electrical discharging. This is because of the fact that electrical discharges involve in oil degradation and thus introduce the decay particles in the oil. These decay particles will affect oil transparency to the light. However, the increase in turbidity in the case of fresh synthetic ester is better as compared to fresh mineral oil. It is noticed that the turbidity of Prop. A and bad oils (both mineral and synthetic) increased with respect to aging. However, the simulation of high energy discharge in Prop. A and bad class oils lead to a reduction of turbidity for mineral oil and synthetic ester. The possible reason for this reduction could be due to an agglomeration and crumpling of the small size and large size decay particles (cellulose particles), respectively. The cellulose particles and decay products in oil may be split or crumple due to sudden and high-energy discharges (100 breakdowns). Also, with increased ionization in the test cell, there would be a large scope for free radicles. This phenomenal increase and decrease in turbidity of the insulating oils is foreseen by particle count studies.

4.3.1.3 PARTICLE COUNT (ASTM D 6786)

It is known that decay particles in oil increase with the degradation of oil-paper insulation caused by aging. The concentration of decay particles is distributed non-uniformly within the available oil volume. These particles have an irregular shape and different sizes. The presence of large size particles is more detrimental than the presence of small size particles. However, most of these particles are conductive in nature and increase the dielectric losses of an insulating fluid. Hence, it is essential to understand the presence of these particles as a function of size. In the present study, a programmable particle counter is employed as per ASTM D 6786 to monitor the number of particles present in various oils. The details of particles count for fresh, Proposition A class, and bad class before and after high energy discharging for mineral oil and synthetic ester are shown in Figure IV-11 and Figure IV-12. For fresh mineral oil and synthetic ester, there is a significant increase in the particle count with high-energy discharging (100 breakdowns).

It is to be noted that fresh oils have no cellulose components present in oils, unlike in aged oils. This is the reason why the increase in large size particles is too low in fresh oils even after discharge simulation. The increase in small-diameter particles is only due to the formation of free radicals and subsequent agglomeration of these free radicals to form decay particles [54]. For aged mineral oil (prop. A and bad classes), a significant increase in small-diameter particles and reduction of large diameter particles is noticed. The reduction of large diameter particles may be attributable to crumpling or splitting of cellulose particles and agglomerated decay particles under the influence of the high-energy discharges [54]. Further, it is also possible that cellulose particles act as filters or absorbing media under the influence of electrical discharges and absorb the decay content in certain cases, as reported in [138]. This will certainly lead to an increase in smaller particles which is evident in the above results. Therefore, the increase in smaller diameter particles may be due to the agglomeration of cellulose particles, free radicals, and other decay contents in the oil under the influence of discharge energy. The non-uniformity in the particle distribution with respect to aging is to be addressed with the artificial addition method adopted to create a different class of oils. Also, the degradation that is occurred in the cellulose insulants will not be uniform even though the degradation conditions are similar. Hence, cellulose insulants play a vital role in the generation of different decay particles and deciding the detrimental factors for the insulation system.

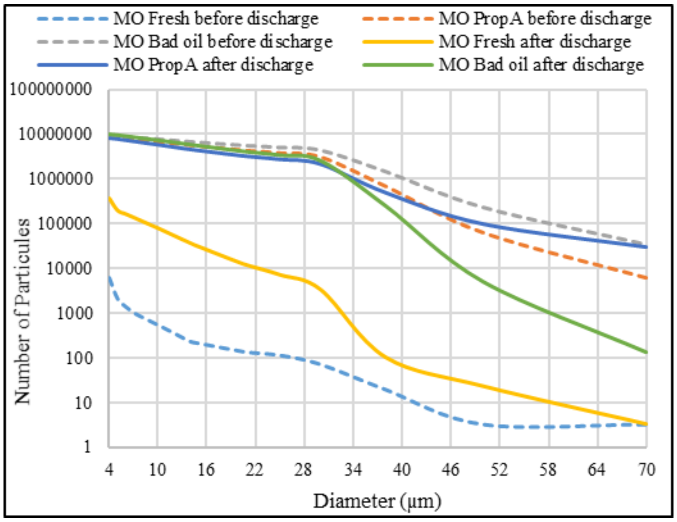


Figure IV-11: Change in the number of particles for mineral oil at different aging conditions with high energy discharge.

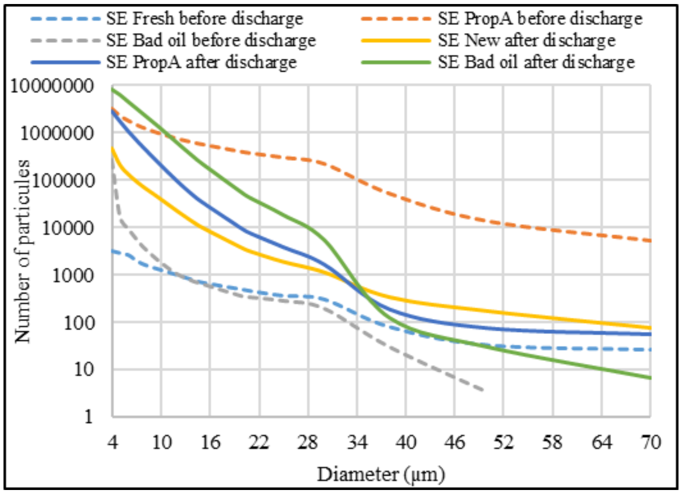


Figure IV-12: Change in the number of particles for synthetic ester at different aging conditions with high energy discharge.

4.3.2 DISSOLVED GAS ANALYSIS

Dissolved gas analysis is a powerful tool to understand the type of gases generated under the faulty conditions. In the present work, after repeated 100 breakdowns, i.e., high-energy discharge, an oil sample of 30 ml is sampled with a glass syringe from the high-voltage discharge cell. This 30 ml oil sample has been subjected to dissolved gas analysis to understand the gases generated due to discharging activity. The per unit (p.u.) values of the dissolved gases are plotted in Figure IV-13 and Figure IV-14. In order to have a proper interpretation of the changes, it was decided to plot in p.u. in log scale. It is seen that for SE, all gases were increased except O_2 and N_2. From the fresh class of oil to bad class of oil: CO_2 increased 4 times, CO increased 44 times, C_2H_6 increased 198 times, C_2H_4 increased by 81 times, C_2H_2 increased 5 times, and H_2 increased 20 times.

Similarly, for MO, all the gases were increasing other than O2 and N_2. CO increased 108 times from new oil to bad oil. While C_2H_6 increased 31 times, C_2H_4 increased 21 times. C_2H_2 increased 2 times and H_2 increased 2 times. It is to be mentioned that reference for p.u. is based on the gas values for fresh oil.

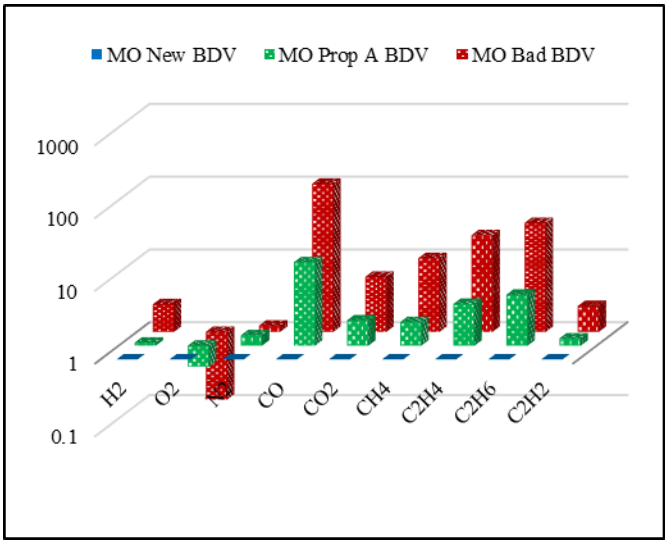


Figure IV-13: Change in the generation of dissolved gases (p.u.) for mineral oil at different aging factors under high-energy discharge.

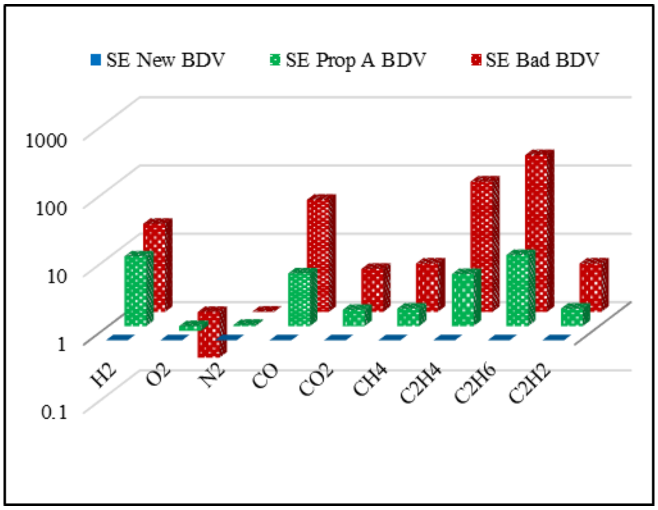


Figure IV-14: Change in the generation of dissolved gases (p.u.) for synthetic ester at different aging factors under high-energy discharge.

The increases in CO and CO_2 is seen because of degradation witnessed by the quantity of cellulose particles present in the degraded oil. The increase in acetylene and hydrogen is attributed to the high-energy discharging activity. This continuous high arc lead to high ionization energy within the oil and generates free radicles such as H• and CH•. These free radicles recombine with the time that leads to H_2 and C_2H_2 as shown below.

$$H\bullet + H\bullet \Rightarrow H_2 \quad (4.1)$$

$$CH\bullet + CH\bullet \Rightarrow C_2H_2 \quad (4.2)$$

Similarly, the formation of ethane and ethylene is due to the recombination of CH3• and CH2• free radicles, respectively.

These fault gases are further evaluated using Duval triangle and Duval pentagon methods. The Duval triangle uses three gases: CH_4, C_2H_4, and C_2H_2, to distinguish mainly between different types of electrical and thermal faults [99] [153]. The analysis of the fault gases based on Duval triangle and Duval pentagon fault analysis is presented in Figure IV-15 to Figure IV-18.

The trending of the fault gas with aging as per the Duval triangle and Duval pentagon is similar for both SE and MO. A clear shift is seen from the fresh oil to bad oil that goes from D1 area (electrical discharge of low-intensity faults) to D2 area (electrical discharge of high-intensity faults). It is explained by the increases of C_2H_4 in ratio compared with the decreases of C_2H_2 and CH_4. The C_2H_2 and C_2H_4 are used in analysis methods to represent high energy faults and high-temperature faults [39]. Change in H_2 represents very low energy faults like the initiation of partial discharges. CH_4, is also representative of such faults and is always formed in addition to H_2.

The Duval Pentagon representation uses five hydrocarbon gases: H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 [150]. Duval pentagon may be used alone, and it is not intended to replace the Duval triangle for oils; rather, it is to reveal complementary information. The results of Duval pentagon are in accordance with Duval triangle for both MO and SE. Importantly, it is to be noticed that for moderately aged oil, the fault classification is D2 from mineral oil and it is in D1 for synthetic ester [100]. This presents the phenomenal behaviour of ester fluids under electrical fault conditions. The following figures are the updated ones and some of the below are different from those that are published in the literature by the author of this thesis.

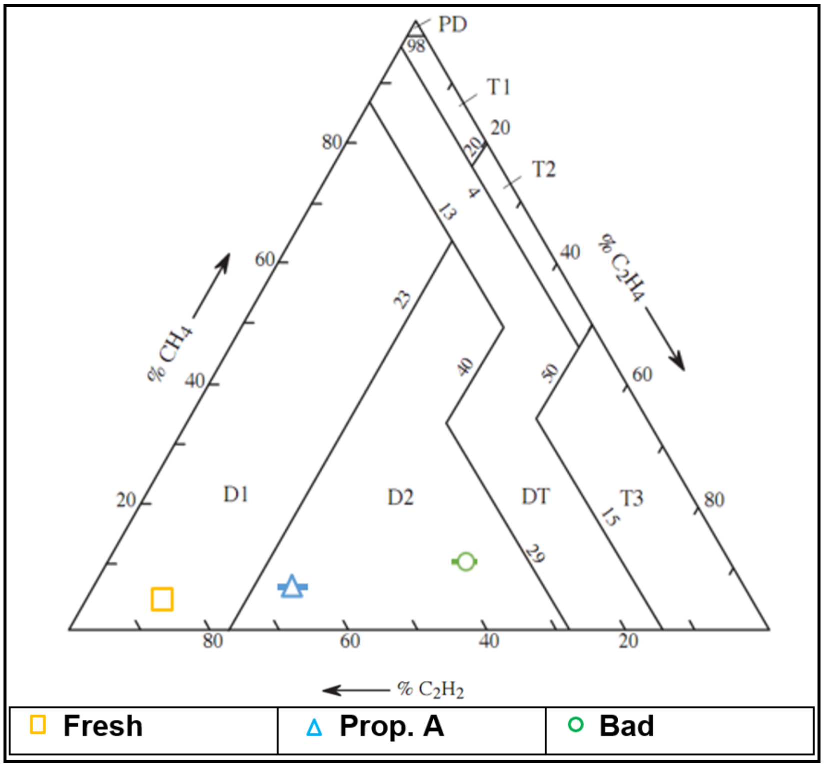


Figure IV-15: Representation of fault gases in Duval triangle for mineral oil.

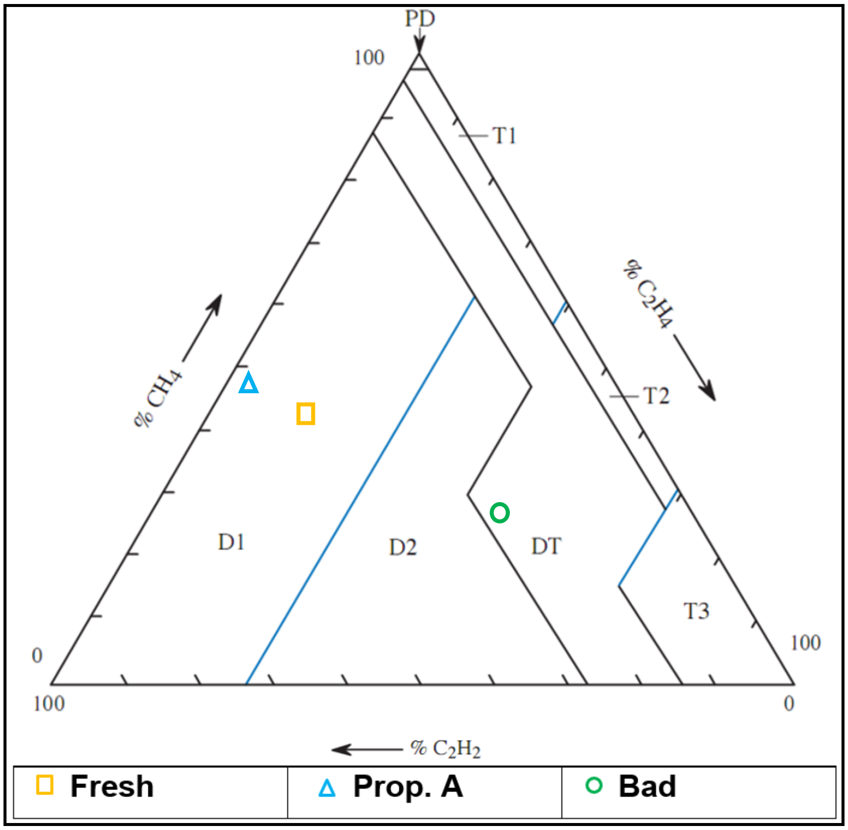


Figure IV-16: Representation of fault gases in Duval triangle for synthetic ester.

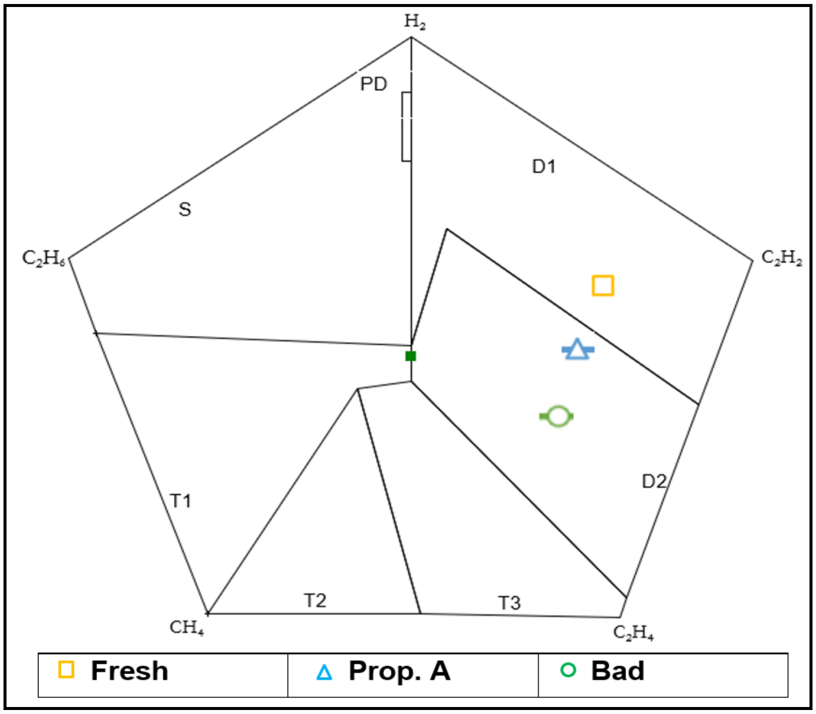


Figure IV-17: Representation of fault gases in Duval pentagon for mineral oil.

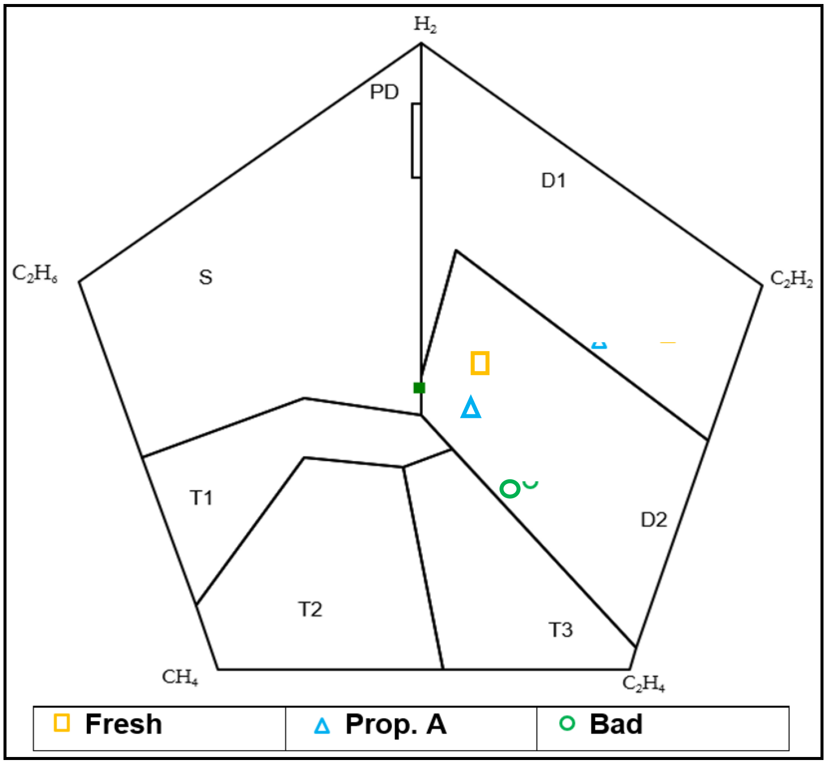


Figure IV-18: Representation of fault gases in Duval pentagon for synthetic ester.

4.4 CONCLUSION

The behaviour of mineral oil and synthetic ester at different aging factors under high-energy discharge electric fault conditions is studied. The influence of such faults on the oil degradation and gassing tendency with oil aging factor has been the subject of focus. Oil degradation is analyzed by turbidity, the concentration of dissolved decay products, and particle count. The influence of high-energy discharge faults on oil degradation at different aging factors is better in the case of synthetic ester as compared to that of the mineral oil. The gassing behaviour of MO and SE under high-energy discharge fault conditions is reported by Duval triangle and pentagon methods for dissolved gas analysis. The behaviour of MO and SE with aging under high-energy electrical fault conditions is almost similar. However, the intensity of fault classification is higher in mineral oil than a synthetic ester. Also, the increase in combustible gases in mineral oil increased rapidly with aging, whereas in synthetic ester, the traces of combustible gases are significant only at higher ages.

Chapter V

GASSING TENDANCY OF FRESH AND AGED MINERAL OIL AND ESTER FLUIDS UNDER ELECTRICAL AND THERMAL FAULT CONDITIONS

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GASSING TENDANCY OF FRESH AND AGED MINERAL OIL AND ESTER FLUIDS UNDER ELECTRICAL AND THERMAL FAULT CONDITIONS

Résumé

Nous savons que les facteurs opérationnels affectent la santé d'un transformateur de puissance en service et réduisent les capacités et la disponibilité pour le transport et la distribution d'énergie. Par conséquent, il est important de comprendre la vitesse de dégradation et les aspects comportementaux correspondants de différents fluides isolants dans diverses conditions de défaut. Dans cet article, le comportement de l'huile minérale et de deux fluides verts (un ester synthétique et un ester naturel) est décrit dans des conditions d'arc, de décharges partielles et de défaut thermique. L'arc est simulé par 100 claquages répétés, les décharges partielles par des décharges électriques de 9 kV pendant cinq heures et les défauts thermiques par des points chauds locaux respectivement, le tout en utilisant différentes configurations en laboratoire. Certaines propriétés physico-chimiques ainsi que la tendance au gazage des liquides isolants frais et vieillis sont étudiées après les différentes conditions de défaut. La spectroscopie UV et les mesures de turbidité sont utilisées pour rapporter le comportement de dégradation et l'analyse des gaz dissous est utilisée pour comprendre la tendance au gazage. Les variations du taux de dégradation de l'huile sous l'influence de divers défauts et les gaz dissous correspondants générés sont analysées. Les générations de gaz de défaut sont diagnostiquées par les méthodes du triangle et du pentagone de Duval pour les huiles minérales et non minérales. Nous en déduisons que la tendance au gazage des fluides diélectriques évolue en fonction de la vitesse de dégradation et dépend de l'intensité et du type de défaut. Il est bien entendu que l'appareil simule les défauts et ne représente pas l'ensemble des phénomènes qui se produisent dans le fluide.

Abstract

Operational factors are known to affect the health of an in-service power transformer and to reduce the capabilities and readiness for energy transmission and distribution. Hence, it is important to understand the degradation rate and corresponding behavioral aspects of different insulating fluids under various fault conditions. In this article, the behavior of mineral oil and two environmentally friendly fluids (a synthetic and a natural ester) are reported under arcing, partial discharges, and thermal fault conditions. Arcing, partial discharges and thermal faults are simulated by 100 repeated breakdowns, top oil electrical discharge of 9 kV for five hours, and local hotspots respectively by using different laboratory-based setups. Some physicochemical properties along with the gassing tendency of fresh and aged insulating liquids are investigated after the different fault conditions. UV spectroscopy and turbidity measurements are used to report the degradation behavior and dissolved gas analysis is used to understand the gassing tendency. The changes in the degradation rate of oil under the influence of various faults and the corresponding dissolved gases generated are analyzed. The fault gas generations are diagnosed by Duval triangle and pentagon methods for mineral and non-mineral oils. It is inferred that; the gassing tendency of the dielectric fluids evolve with respect to the degradation rate and is dependent on the intensity and type of fault. It is to be understood that the apparatus simulate the faults and does not represents the entire phenomenons that happens in the fluid.

5.1 INTRODUCTION

Alternative dielectric fluids for use in oil-filled apparatuses is a topic of concern for industry and utilities for decades. Ester dielectric fluids (both natural and synthetic ester) are being investigated for use in oil-filled transformers. The dielectric properties and rate of deterioration of ester fluids is comparable to those of mineral insulation oils used in power transformers [30]. The compatibility of these alternative fluids with solid insulants was investigated and reported possible longevity of cellulose insulants when used with ester dielectric fluids [154]. The pre-breakdown phenomena, workability, influence of temperature, compatibility with other transformer materials, and service experience were reported by various researchers [30] [36] [61] [79]. Several researchers also attempted to understand the regeneration aspects and end of life criteria of these insulating fluids [155]. From the extensive laboratory studies, IEEE Standards and CIGRE reports came to the acceptance of using these fluids in oil-filled transformers [156] [157] [158]. However, condition monitoring and diagnostic tools for ester-filled transformers is still a topic of high interest for the industry. Meanwhile, the possibility of ester fluids to be miscible with mineral insulating oils was a topic of research to understand the feasibility of retro filling existing units. Fofana et al. [42, 159] reported the properties of various mixtures of mineral oil and ester fluids extensively. Later, U. Mohan Rao et al. [126] [160] reported the long-term degradation behaviour, degradation solid insulation in mixture insulating fluids. Nevertheless, ester fluids are being used in oil-filled transformers and various utilities across the globe started filling/retrofilling some new and existing transformers with ester liquids. There is a large scope for research including, but not limited to, the understanding of the behavior of these insulating fluids under different operating conditions, regeneration aspects, and condition monitoring aspects.

Despite due care is taken by manufacturers and utility, yet there is a high probability for electrical discharges and local hotspots. The presence of electrical discharges and local hotspots for longer duration leads to high electrical discharge and thermal failures. The electrical faults are low and high-energy discharge electrical faults, which are treated as corona discharges, partial discharges, and breakdown. Thermal faults are the accumulation of heat over a local area and are treated as hotspots. Both electrical and thermal faults are originated due to various reasons including, dielectric defects, air bubbles, impurities, sharp edges, and any manufacturing defects. The presence of these faults hampers the integrity of the insulation system in various aspects and is detrimental to a transformer. Therefore, early detection of these faults is of high importance to condition monitoring engineers and maintenance planners. It is well established that these faults are involved in the generation of several gases that are dissolved in the oil. Therefore, the dissolved gas analysis is seen as one of the important conditions monitoring and diagnosis tools.

Numerous researchers have reported the gassing tendency of various dielectric liquids under different fault conditions. The tendency to gassing generation under partial discharges or low energy discharge electric faults in mineral oils and ester fluids were investigated and reported in [108] [109] [106]. It is reported that higher quantities of C_2H_2 and H_2 are generated in natural esters and C_2H_2 remains the key gas to indicate a defect or fault witnessed by electrical discharges. Also, the influence of high energy discharges on the gassing tendency of the dielectric fluids have been reported in [108] [112] [111]. Similar to the low energy discharge faults, H_2 and C_2H_2 are found to be witnessed due to arcing fault conditions. However, a large amount of C_2H_2 is generated as compared to the low energy discharge cases. The gassing tendency of ester fluids under thermal faulty condition was also investigated and are reported in [108] [109] [111] [115] [116]. It is found that natural ester generates more gases at a higher temperature (> 300 °C) and traces of C_2H_6 are found increasing with increasing temperature. The key gases in ester fluids under thermal faults are found to be CH_4, C_2H_4, CO, and C_2H_6. However, there are different methods for simulating the hotspot at different temperatures; the gassing tendency of the dielectric fluid varies accordingly. The details of which are critically analyzed and summarized in [117]. It is to be mentioned that the fault diagnosis approaches discussed above are limited to a single fault i.e. electrical or thermal fault alone. However, in the real transformer, there are possibilities for the electrical and thermal faults to occur simultaneously. Thus, in [161] a combination of electrical and thermal faults was studied. The authors reported the gassing tendency at different combinations of electrical and thermal faults while varying fault temperatures and fault voltages. The trending of fault gases has been explicitly reported under different laboratory conditions.

Electrical discharges, electrical arcing, and thermal faults in a transformer influence the degradation of the oil accompanied by faults gas generations. These faults also, expedite the degradation reactions in a transformer, which together with acids and heat accelerate deterioration of the insulation system. It is to be understood that the intensity of this degradation process and fault gases are also attributable to the condition of the oil. In other words, the occurrence of the same fault with the dielectric fluid at two different conditions (age) will have different levels of consequences. Recently, authors from our research group have reported the influence of aging on the gassing tendency and oil's degradation under low energy electrical discharge faults for mineral oil and synthetic esters [39].

It was reported that the condition (age) of the oil has a significant influence on the concentration of the dissolved gases which affects the fault diagnostic conditions. Also, the influence of thermal aging on the gassing tendency of mineral oil and natural esters under the influence of thermal faults has been reported in [115]. A significant change in the dissolved gas concentration has been noticed with an increase in the thermal aging duration of the dielectric fluids. Hence, there is a need to study the gassing behavior of ester-based dielectric fluids (both natural and synthetic ester) under the influence of electrical and thermal fault conditions at different aging conditions and the influence of the faults on oil degradation. Therefore, the present research is aimed to understand the influence of aging or state of the dielectric liquid on gassing tendency under different operating faulty conditions. The authors have also focused the influence of different faults on the degradation of the dielectric fluids. In the present work a mineral oil, a synthetic ester, and a natural ester have been investigated under low electrical energy discharge, high electrical energy arcing, and hotspot faulty conditions. The degradation of the insulation liquids is monitored by adopting UV spectroscopy and turbidity measurements as per ASTM D6802 and ASTM D6181 standards test methods. The Dissolved gas analysis is performed as per DGA as per ASTM D3612.

5.2 EXPERIMENTAL SET-UP

5.2.1 SAMPLES

For the present study, a mineral oil (MO), a natural ester (NE), and a synthetic ester (SE) have been adopted. The properties of the fresh unused oils considered for this study are tabulated in Table V-1.

Table V-1: Significant properties of the unused base oils used in this study

Parameters	MO	NE	SE
Power Factor 50 Hz 90 °C, IEC 60247	<0.001	-	<0.008
Water content (ppm), IEC 60814	<20	<50	<50
Viscosity (cSt @ 40 °C), ISO 3104	9.2	32	29
Fire point (°C), ISO 2592	-	>350	316
Flash point (°C), ISO 2719	148	>260	260
Pour Point (°C), ISO 3016	-54	-18	-56
Acidity, (mg KOH/g), IEC 62021	<0.01	< 0.04	<0.03
Density at 20˚C (kg/dm3)	0.869	0.92	0.97

Unused mineral oil, synthetic ester, and natural ester have been subjected to thermal aging according to a modified ASTM D1934 standard method at 115 °C for 2000 hours. The thermal aging is performed with the copper catalyst (3g/l) and cellulose Kraft papers (1:20). After the thermal degradation procedure, highly degraded oil/paper insulation is subjected to sonication for 30 seconds using Qsonica Q1375 Sonicator. This sonication allowed to prepare a gentle solution of degraded oil and paper. Further, the individual solutions of MO, NE, and SE are separately added to unused MO, NE, and SE respectively. The proportions of the degraded solution added to unused oils allowed controlling the acid values of the oils. This facilitated having oil samples with a specific level of acidity that refers to a bad class of the oil aging as per [131].

It is to be mentioned that attaining a predetermined value of acidity is not feasible with the traditional thermal aging process. Therefore, the authors prepared a degraded solution which is later used to obtain a specific value of the acidity by adding it in suitable proportions. Now, these aged oils (obtained with the desired acidity values) along with fresh unused oils are used for the present study. The details of the acidity measurements of the bad class are illustrated in Table V-2.

Table V-2: Details of acidity measurements of bad class insulating liquids

Sample	Acidity test 1 mg KOH/g	Acidity test 2 mg KOH/g	Average	Std. deviation	Ratio of degraded solution to Fresh oil*
MO Bad Class	0.2757	0.2675	0.2716	0.0058	1:26.6
SE Bad Class	0.2314	0.2573	0.24435	0.0183	1:20
NE Bad Class	0.3016	0.2801	0.29085	0.0152	1:40

* ratio adopted for this study

5.2.2 LABORATORY SIMULATION OF ELECTRICAL AND THERMAL FAULTS

5.2.2.1 HIGH ENERGY DISCHARGES (ARCING)

High energy discharge faults are stimulated by repeated breakdowns to produce arcing in the oil volume. The breakdown of the insulation fluid is performed in the laboratory as per ASTM D 877. To simulate the sustainability of the arcing fault, 100 breakdowns have been performed with 2 minutes of break between each breakdown. To understand the impact of high-energy discharge electrical faults, dissolved gas analysis is performed after 100 continuous breakdowns. To understand the influence on oil degradation, UV spectroscopy and turbidity measurements are reported before and after 100 breakdowns. The details of the breakdown test set up are presented in Figure V-1 and the series of breakdowns for MO, NE, and SE for fresh and aged oils are shown in Figure V-2. In addition, the total average energy used for 100 breakdowns in various liquids is tabulated in Table V-3.

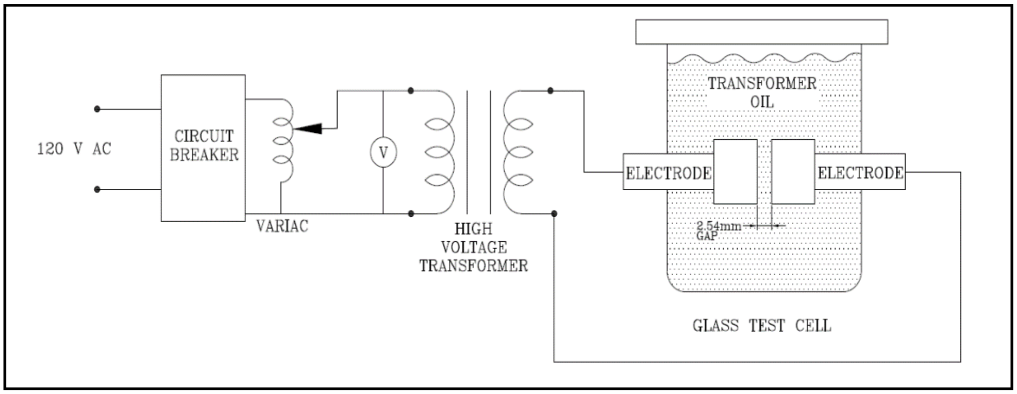
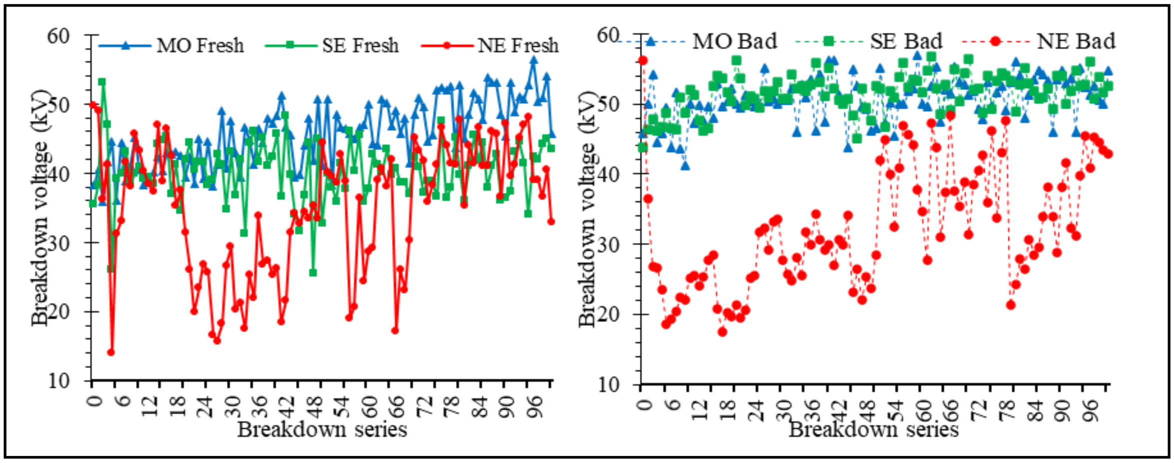


Figure V-1: Test set up used for Experimental of the arcing fault in various dielectric fluids.



a) b)

Figure V-2: Experimental of the arcing fault in various dielectric fluids; a) 100 BDV series for fresh insulating liquids; b) 100 BDV series for aged insulating liquids.

Table V-3: Details of Energy for 100 BDV’s

Sample	MO Fresh	MO Bad	SE Fresh	SE Bad	NE Fresh	NE Bad
Average energy used for 100 BDV’s (Joules)	4.53×10^{-1}	5.53×10^{-1}	4.40×10^{-1}	7.11×10^{-1}	3.50×10^{-1}	2.97×10^{-1}

It is observed that breakdown of the dielectric liquids is increasing with aging and with the number of breakdowns. To understand this, it is to be recalled that water saturation limit of dielectric liquids increases with increase in aging [150]. Also, breakdown voltage is dependent on relative moisture content and hence breakdown voltage of the aged oil will be higher than that of the fresh oil at a given absolute moisture content. Under AC stress, a field-induced drift of particles, located in high field regions, can be entailed by a stress relieve leading to an improvement of the dielectric strength, compared to technically clean oil [152]. In the same way, breakdowns cause definite degradation; this will lead to an increase in the water saturation on average with breakdown times.

5.2.2.2 LOW ENERGY DISCHARGES (PARTIAL DISCHARGES)

Low energy discharges electrical faults are often called partial discharges, which could be internal discharge, surface discharge, and corona discharges. In the present work, a laboratory set up has been used to produce a surface discharge of 9 kV. A 9 kV electrical discharging activity is simulated for 5 hours on the surface of the dielectric fluid. The free electrons are generated by a cylindrical copper electrode sealed in a 500 ml Erlenmeyer glass. The electrode is placed in the center of the discharge cell and suspended above the oil’s surface. The distance between the central electrode and the surface of oil is approximately one inch. The details of the experimental set-up was reported by the authors from our research group in [39] and is shown in Figure V-3. The discharge is initiated after vacuuming the test cell and the changes in the pressure with discharging time are recorded to understand the gassing behavior of the insulating fluid. This method is useful in understanding the stability of the insulating fluids to gassing behaviour. The pressure changes in the test cell with fresh and aged MO, NE, and SE as a function of discharging time are shown in Figure V-4.

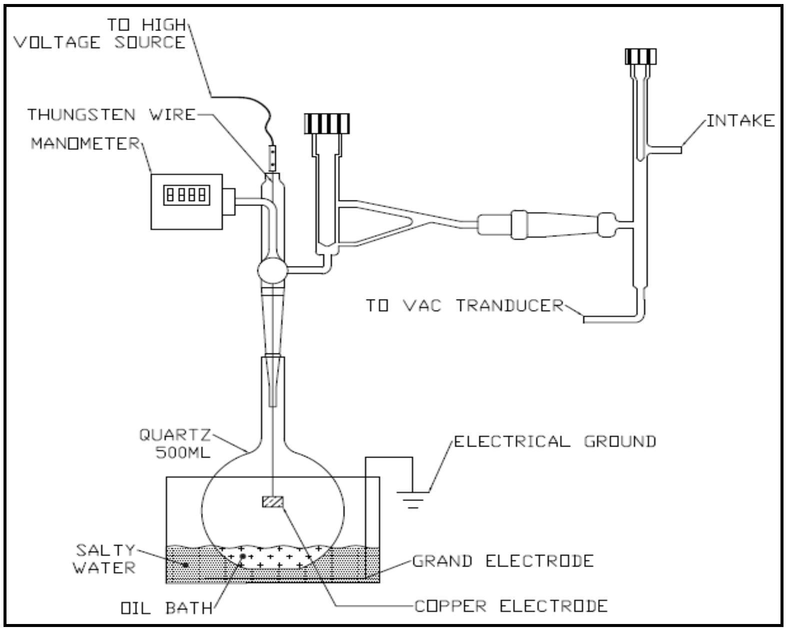


Figure V-3: Experimental test set up of the low energy discharging.

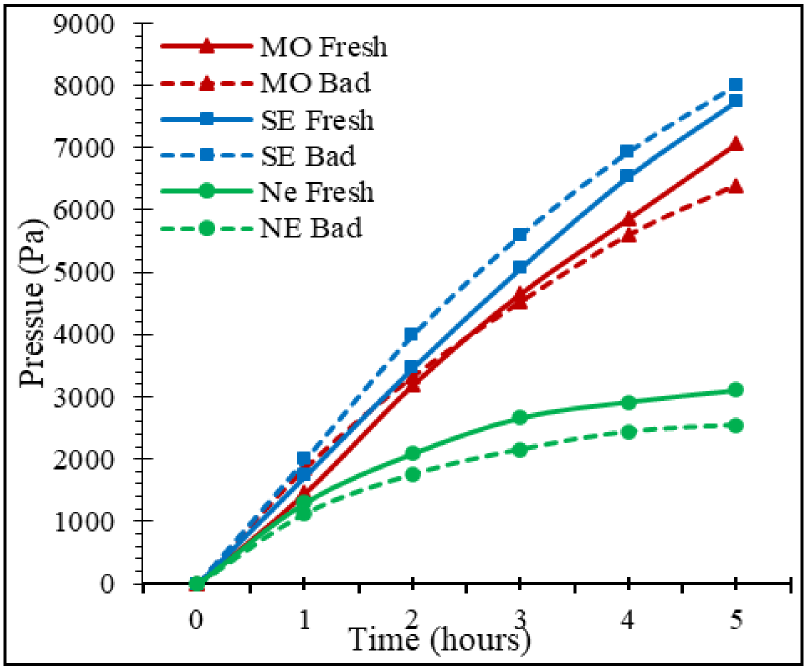


Figure V-4: Gassing tendencies for fresh and aged fluids under electrical discharges.

5.2.2.3 THERMAL FAULTS (HOTSPOT)

Thermal faults or hotspots simulation in MO, NE, and SE have been simulated by developing a laboratory-based test set up. The setup used for simulating thermal faults is presented in Figure V-5. The set up consists of a borosilicate-glass vessel and a Teflon cover with bushings to hold the heating element. Constantan was chosen for the heating element for its flat resistivity on a large scale of temperature. The input supply is connected to a variac that feeds two high current transformers connected in parallel while the temperature of the wire was regulated by an ammeter and voltmeter connected between the heating element and the secondary. By measuring the voltage and current, the average temperature of the hotspot may be approximated. This is also validated by using a high-temperature resistant thermocouple. An aluminum funnel-shaped structure is placed just over the heating element. This is because the generated gas bubble enters the pipette through this funnel structure according to the Archimedes' principle where they can be measured. In each experiment, a quantity of 800 ml of dielectric fluid was introduced to fulfil the vessel and the pipette up to the reference value. The fluid samples under hot-spot tests are allowed to heat for periods of 30 minutes and the volume of gas generated is recorded. The temperature reached values close to 250 °C, which for the mineral is risky due to its flashpoint. For safety reasons, the current is zeroed until the temperature of the insulating fluid equals the room temperature (~24 °C). This test cycle of 30 minutes of heating and cooling down to room temperature have been repeated for 12 times. For every 30 minutes of the heating cycle, the volume of gas is recorded. The volume of the gases generated as a function of the heating cycles are presented in Figure V-6.

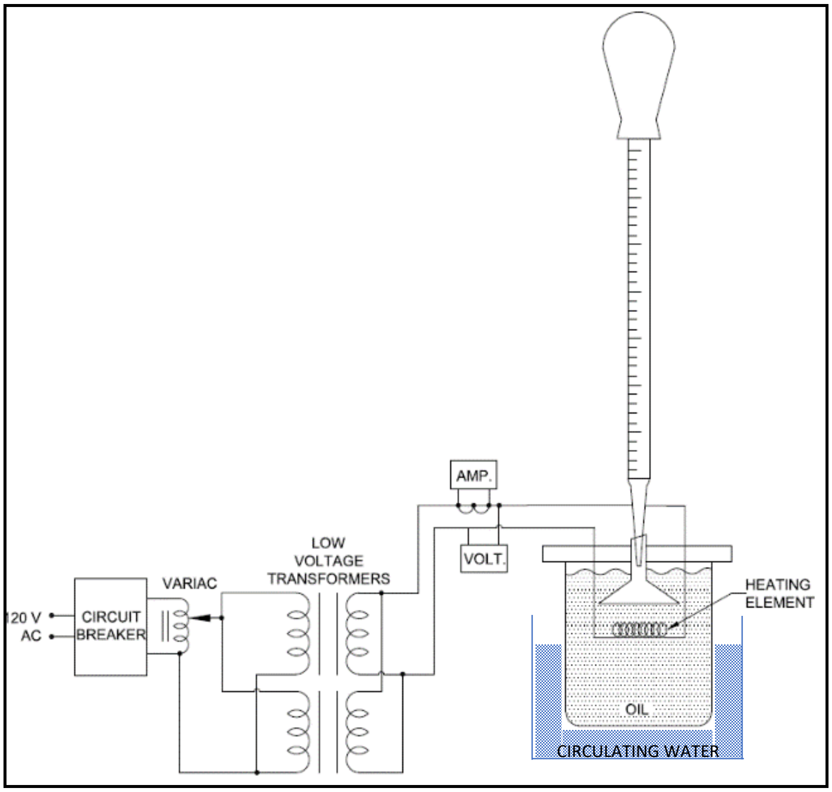


Figure V-5: Experimental test set up of the hotspot fault in various dielectric fluids.

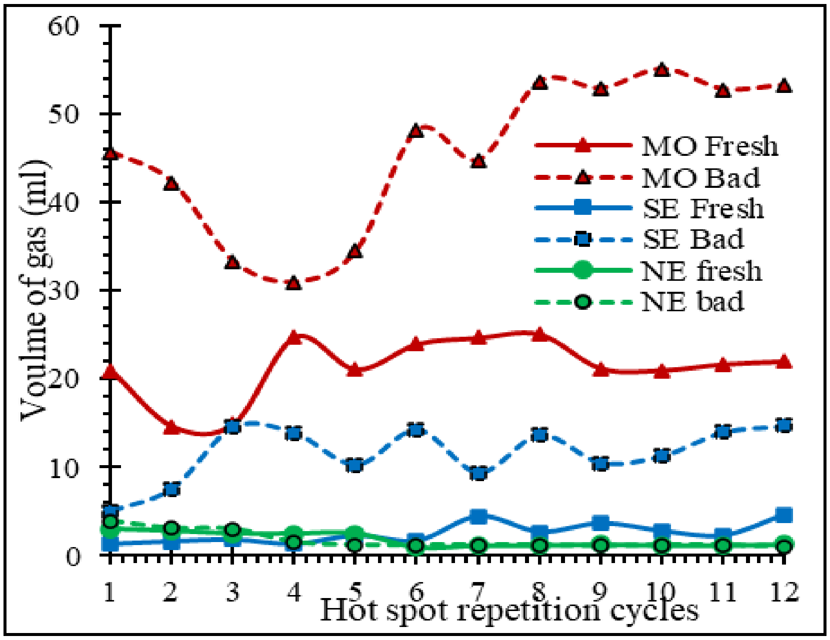


Figure V-6: Gassing tendency under hotspot condition.

5.3 RESULTS AND DISCUSSIONS

The results of the degradation rate of the oil, before and after simulating electrical and thermal faults are discussed in this section. As mentioned earlier, the degradation of the insulating liquids has been understood by Ultraviolet visible spectral curves, dissolved decay contents, and turbidity. The details of the fault gases evolved due to the characteristic faults have been analyzed by dissolved gas analysis and application of Duval's diagnostic methods reported in the literature. To have a clear observation and to avoid direct comparison of various insulating oils, the authors have presented the results oil by oil with all types of faults. Also, it is difficult to obtain similar level of the fault intensity in order to compare fault by fault. Therefore, it is interesting to see the impact of the same type of faults in a dielectric fluid at different aging conditions (Fresh and Bad classes). The following notations presented in Table V-4 are used for representing different cases of the insulating liquids.

Table V-4: List of abbreviations

Abbreviation	Details
MOF	Mineral Oil Fresh
MOB	Mineral Ester Bad
SEF	Synthetic Ester Fresh
SEB	Synthetic Ester Bad
NEF	Natural Ester Fresh
NEB	Natural Ester Bad
BDV	High energy discharge (arcing)
PDS	Low energy discharge (Partial discharge)
HS	Hot spot (Thermal fault)
A	Dissolved decay products
T	Turbidity
TDCG	Total dissolved combustible gases

5.3.1 DEGRADATION OF INSULATING FLUIDS

In the present section, the degradation of fresh and aged oils while subjected to electrical and thermal faults is of concern. Fresh oils are technically clean and are free from decay particles and cellulose particles, and other aging byproducts. Whereas, aged oils contain, cellulose particles, dissolved decay products, acids and other aging byproducts. Therefore, when a fresh oil and aged oil are subjected to different fault conditions, the undergoing chemical perspectives are expected to be different. Subsequently, the influence of these faults on the dielectric fluids will be different. Hence oil absorbance, dissolved decay products, and turbidity are measured for before and after subjecting the liquids to the fault conditions. The details have been presented in Figure V-7 to Figure V-9.

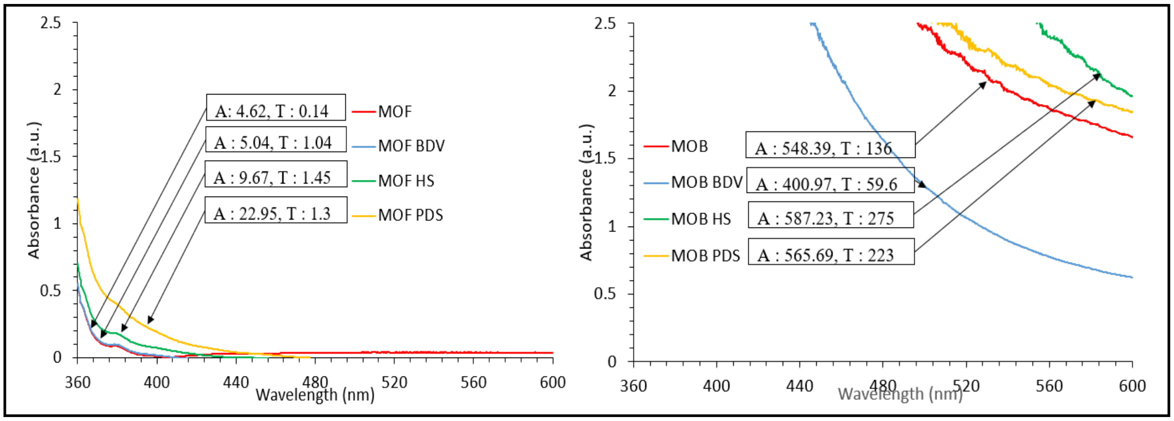


Figure V-7: Illustration of the degradation of the Mineral oil under different fault conditions.

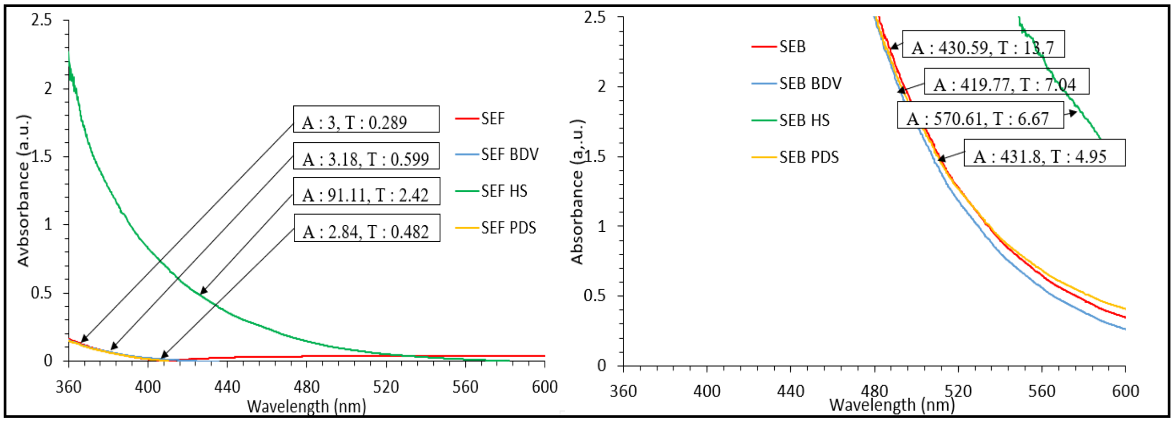


Figure V-8: Illustration of the degradation of the synthetic ester under different fault conditions.

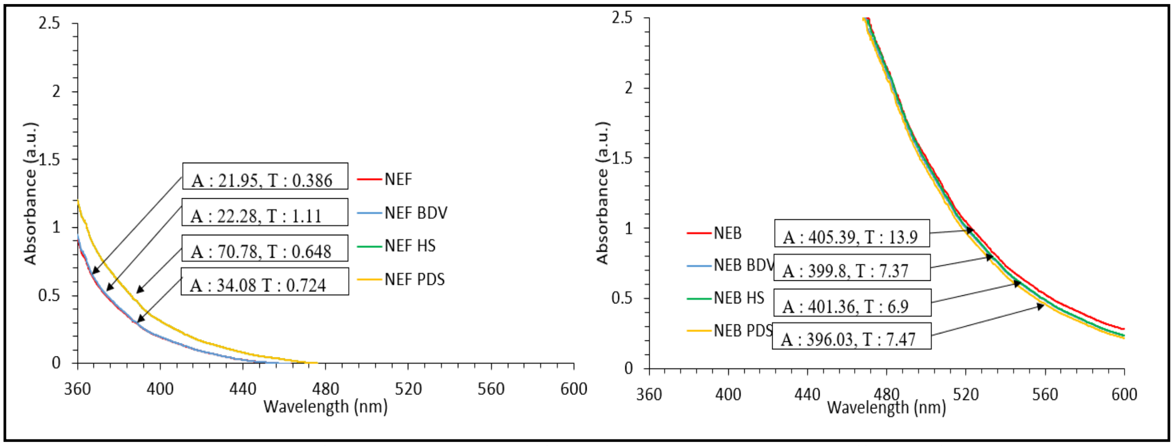


Figure V-9: Illustration of the degradation of the natural ester under different fault conditions.

In fresh oils, the changes that occur due to the application of thermal and electrical faults depend majorly on the thermal stability of the chemical bonds and the ionization potential respectively. In case of aged oils, along with the said factors, the concentration of colloidal and soluble decay particles plays a significant role in further degrading a dielectric fluid. Therefore, in the present research, the concentration of the dissolved decay products and turbidity measurements have been reported. From Figure V-7 to Figure V-9, it is seen that aged oils have a high turbidity, decay content concentration which is obvious. It is to be noticed that the application of fault conditions (both electrical and thermal) had a different impact for fresh and aged oils. In Figure V-7), from fresh mineral oil, the influence of partial discharges is high as compared to arcing and hotspot. Similarly, in the case of aged oils, the hotspot influence is superior to that of the partial discharges and arcing. However, it is seen that the absorbance of aged oil is reduced with arcing. This may be due to the splitting or de-agglomeration of the cellulose particles present in the oil which reduces the absorption to light. To further understand this, the chemical function group analysis is to be understood. The absorbance and turbidity of the aged oil are increasing with partial discharges and thermal faults. From Figure V-8, it is noticed that the influence of hotspot is higher than that of the partial discharges and arcing for fresh and aged synthetic ester. Also, the influence of partial discharges and arcing is too low in the case of fresh and aged fluid samples. One may understand that the influence of electric faults is low when compared to thermal faults in the case of synthetic ester. However, it is to be assured that the intensity of the fault nature is uniform in all three cases. Also, in Figure V-9, the influence of the hotspot is higher when compared to the other faults in the case of fresh natural ester. To understand the influence, faults of much higher intensities are to be evaluated. It is to be recalled that thermal faults involve an increase in local temperature and promoting oxidation of the oil/paper insulation. These generated acids trigger a self-sustained process called hydrolysis which in turn degrades the solid insulation. But, in case of electrical faults, the influence is more associated to a generation of acids and free radicals which leads the degradation. However, both electrical and thermal faults are involved with the generation of dissolved gases. The detailed analysis of dissolved gas analysis is presented in the next section.

5.4 GASSING TENDENCY OF INSULATING FLUIDS

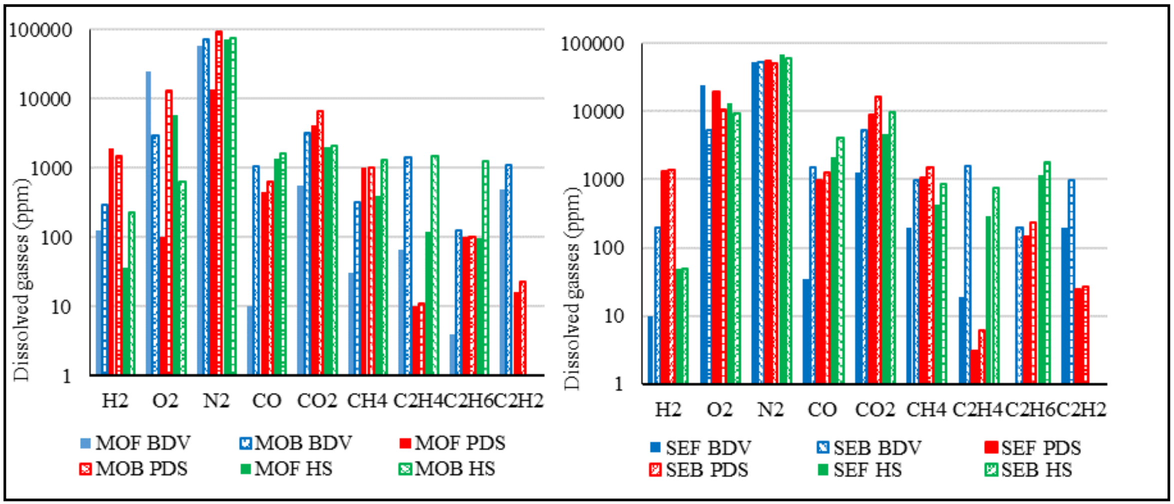
The dissolved gas analysis for mineral oil and non-mineral oils are analyzed according to IEEE C57.104 and IEEE C57.155 respectively. As per of IEEE C57.104 and IEEE C57.155 the following are the observation on gas trending in mineral oil and non-mineral oils respectively for different fault conditions.

Arcing faults: With high energy discharges, traces of C_2H_2 and C_2H_4 increase in mineral oils and C_2H_6 is generated in ester fluids. However, H_2, CH_4, C_2H_4, C_2H_2 are witnessed in common with arcing faults and C_2H_2 need proper monitoring to diagnose arcing failures.

Partial discharge faults: With low energy discharges in the initial stages CH_4 and small traces of C_2H_2 increases and at an advanced stage; traces of C_2H_2 and C_2H_4 raises in mineral oils. In ester fluids, H_2 and C_2H_2 are witnesses. However, severe traces of H_2 remains common in both dielectric liquids. Hence, H_2 and C_2H_2 may be monitored for identifying low energy discharging activities.

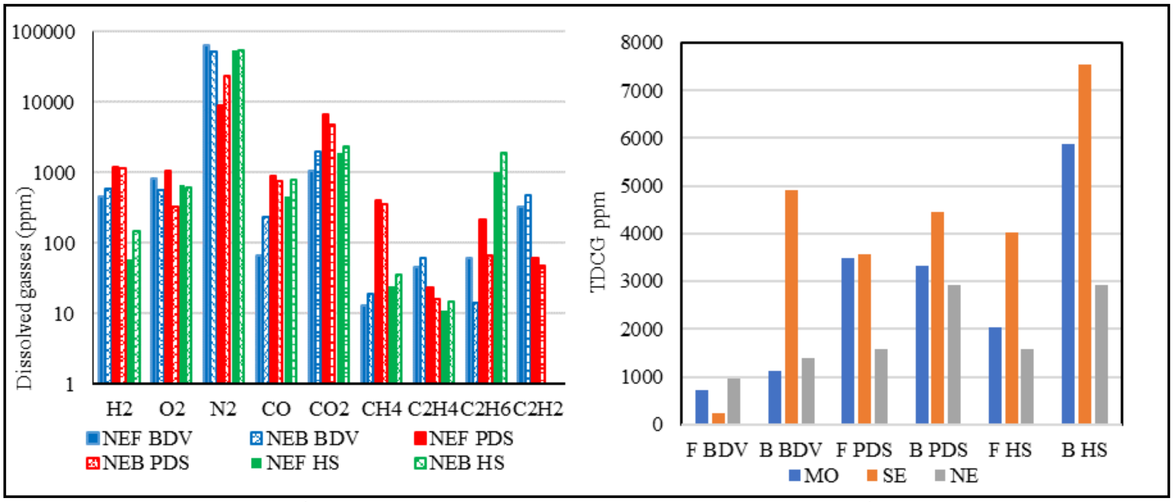
Thermal faults: Local hotspots in mineral oil increases H_2, CH_4, C_2H_4, C_2H_6, and C_2H_2 whereas in ester oil, H_2, CH_4 and C_2H_6 and some C_2H_4 increases.

However, electrical and thermal faults are mostly associated with cellulose insulation and degradation of cellulose is accompanied by a generation of CO and CO_2 gases. Hence, the above discussed faults are also mostly witnessed by CO and CO_2 gases for cellulose-based insulation systems. Also, the influence of aging on the gassing behaviour is not addressed in the said standards. In the present work, dissolved gas analysis has been performed on fresh and aged mineral oil and ester fluids after subjecting to partial discharges, arcing, and thermal hotspot. Hence, the gases generated under the influence of different faults for a dielectric liquid with aging are discussed in this section. The details of the dissolved gases for different oils under different faults for mineral oil, natural and synthetic ester are shown in the Figure V-10 and Figure 11.



a) b)

Figure V-10: Illustration of the results of dissolved gases under different fault conditions; a) Mineral oil; b) Synthetic ester.



a) b)

Figure V-11: Illustration of the results of dissolved gases under different fault conditions a) Natural ester; b) Total dissolved combustible gases.

It is noticed that the concentration of the majority of the gases is higher in case of aged oil under the influence of thermal and electrical faults. For arcing faults, H_2, CH_4, and C_2H_2 are found to increase in all the dielectric fluids. However, O_2 is reduced and significant change is not noticed in the traces of N_2 for fresh and aged oils. Thus, H_2, CH_4, and C_2H_2 gas concentrations vary with the state condition of the oil under arcing faults for mineral oils and non-mineral oils. For partial discharge faults, a much less change in H_2 and C_2H_2 is noticed for fresh and aged oils. This is because, cellulose decay particles act as a filtering and absorbing medium under low energy discharge fault conditions [39]. However, there is almost no change in CH_4, C_2H_4, and C_2H_6 for fresh and aged mineral oil. For ester fluids, a noticeable change in the traces of CH_4, C_2H_4, and C_2H_6 are noticed. Therefore, under partial discharging activity, CH_4, C_2H_4, and C_2H_6 vary with the condition of the ester fluids and H_2 will be generated in common for both the fluids according to the state of the oil. For thermal faults, there is a significant change in H_2, CH_4, C_2H_4, and C_2H_6 in mineral oil while in ester fluids, there is a small change in CH_4, C_2H_4, and C_2H_6. This is because of the fault temperature which is not more than 400˚C and hence a significant change in C_2H_6 and C_2H_2 are not witnessed. Hence, under thermal faults with less temperatures, H_2, CH_4, C_2H_4, and C_2H_6 gases will be generated in common for both the fluids according to the state of the oil. From Figure V-5 b), it is noticed that the generation of combustible gases increase with increasing degradation of the oil. However, the generation of combustible gases are higher for partial discharging and hotspot activity. This is because, the degradation of dielectric fluids is accelerated by cellulose decay particles, and other conductive particles. Therefore, excessive amounts of CO and H_2 increases easily in any event of the fault, thus aiding to the increase in TDCG. The illustration of Duval triangle and Duval pentagon with the fault distribution locations are shown in Figure V-12 to Figure V-17 for mineral oil, natural and synthetic ester. The following figures are the updated ones and some of the below are different from those that are published in the literature by the author of this thesis.

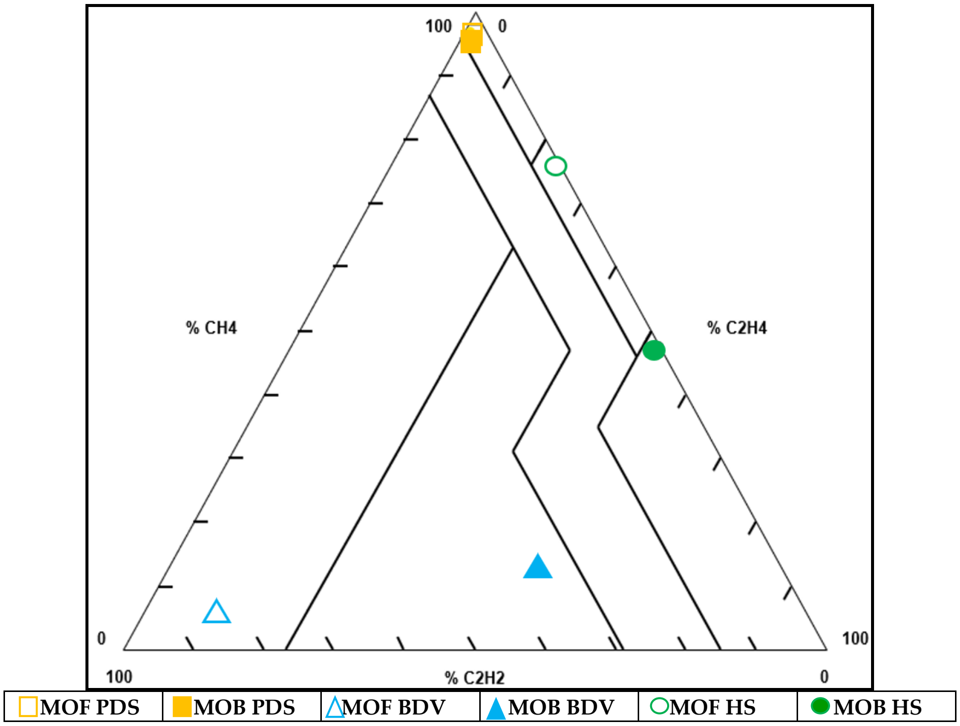


Figure V-12: Illustration of fault gas diagnosis using Duval triangle methods for Mineral oil.

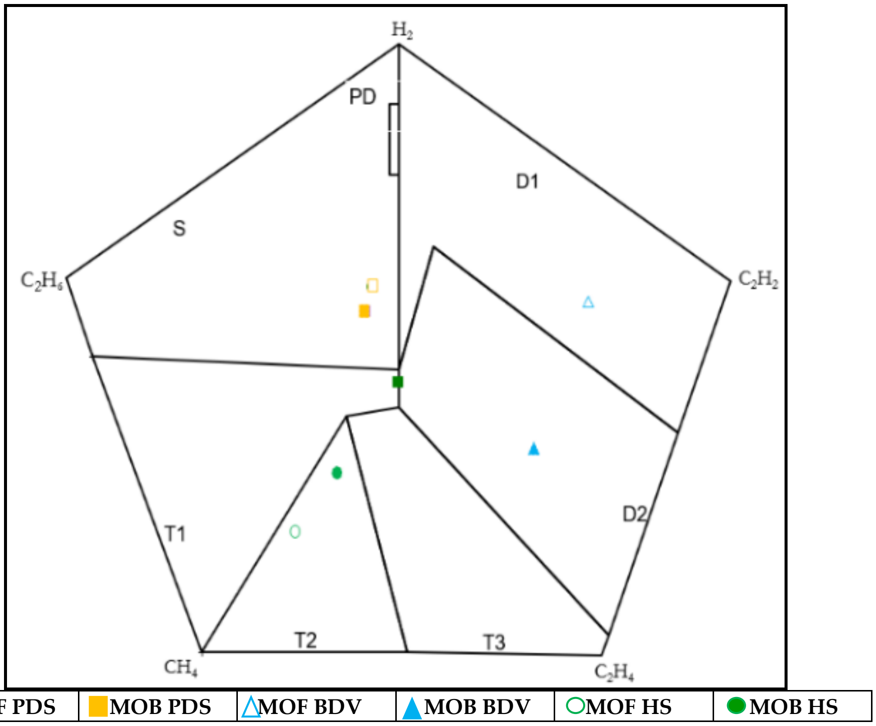


Figure V-13: Illustration of fault gas diagnosis using Duval pentagon methods for Mineral oil

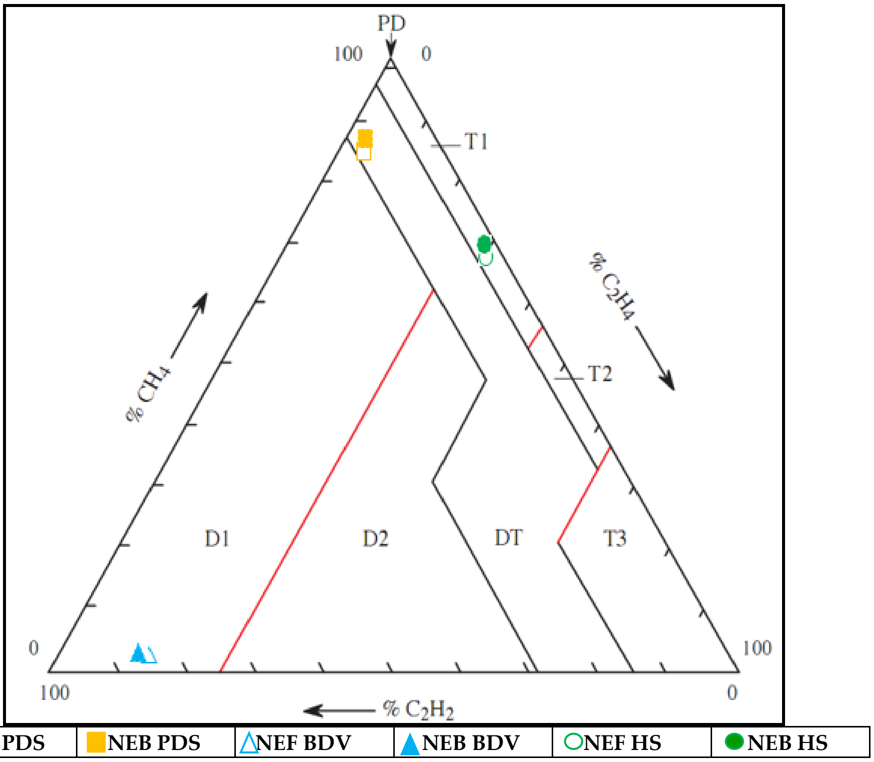


Figure V-14: Illustration of fault gas diagnosis using Duval triangle methods for natural ester

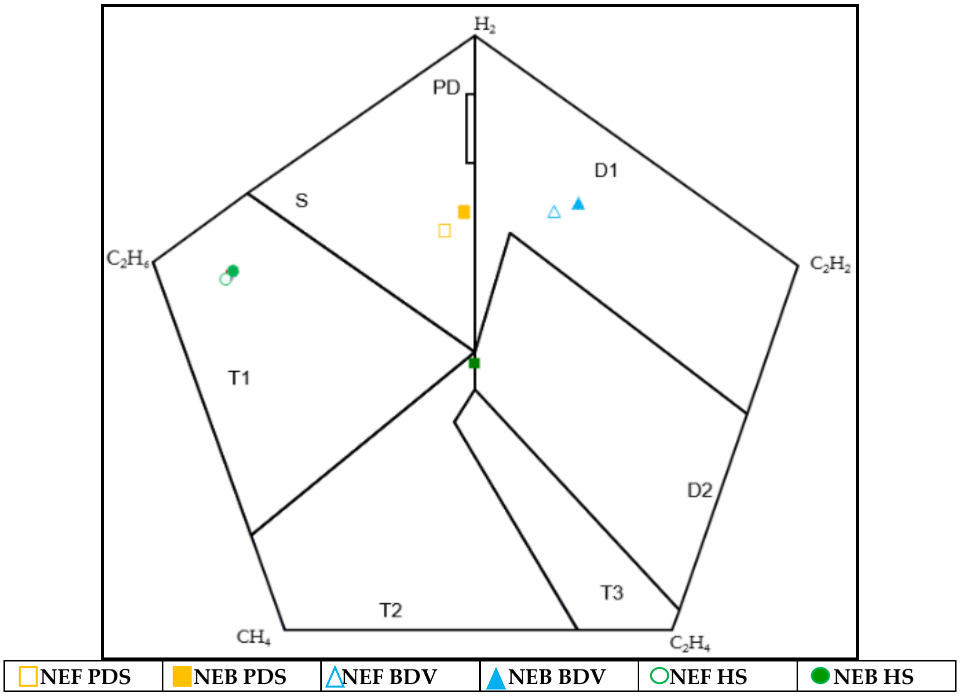


Figure V-15: Illustration of fault gas diagnosis using Duval pentagon methods for natural ester

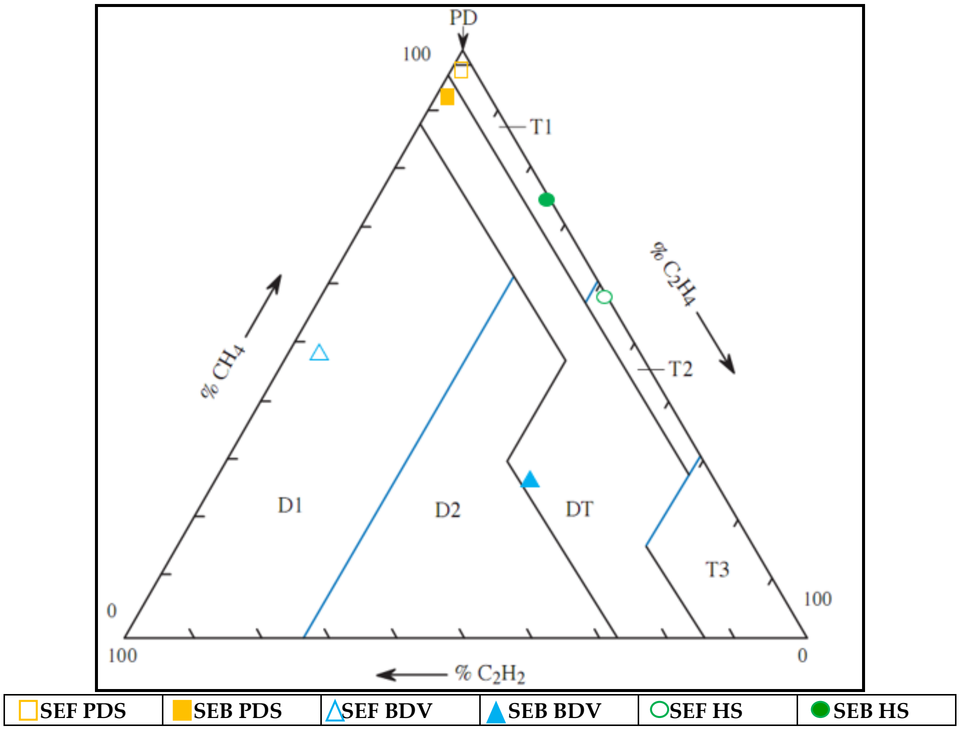


Figure V-16: Illustration of fault gas diagnosis using Duval triangle methods for synthetic ester

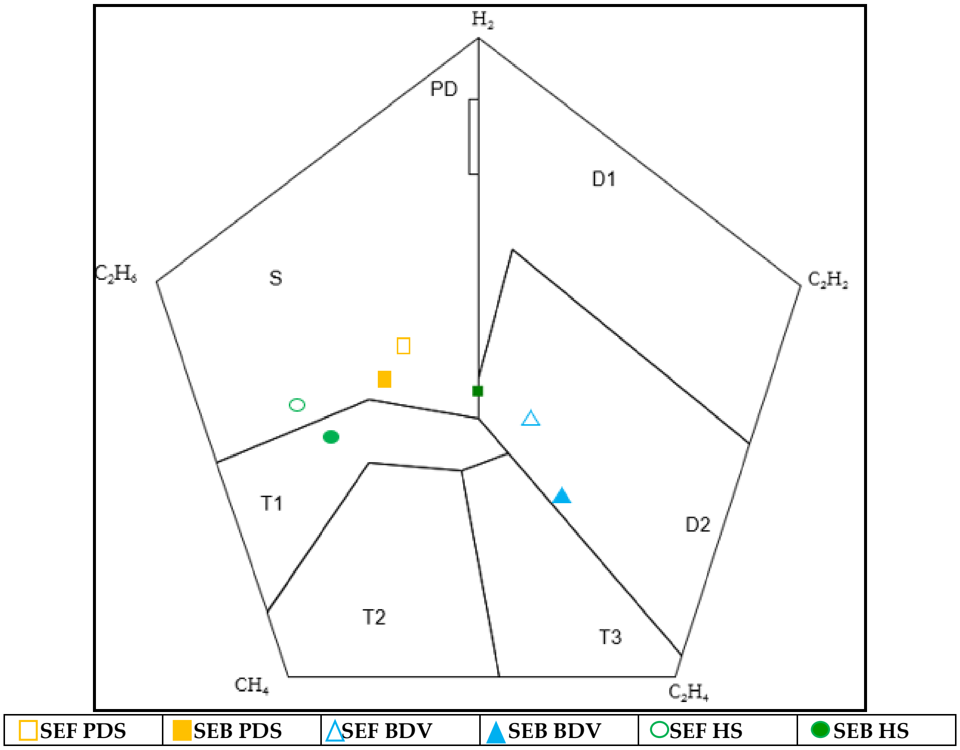


Figure V-17: Illustration of fault gas diagnosis using Duval pentagon methods for synthetic ester

To further understand the influence of the condition of the dielectric liquid on gassing tendencies under different faults, Duval triangle and Duval pentagon methods for mineral oil and non-mineral oils have been applied for mineral oil and ester fluids respectively. Both fault diagnosing methods indicate that faults evolve with degradation duration. However, this phenomenal changing depends on the intensity of fault and the degradation rate of the insulation system. The insulation system degradation rate is highly dynamic and hence the gassing tendency of the dielectric fluid remains dynamic with operation time. Because as per Duval's methods, any disagreement or mismatching in the fault type using triangle and pentagon methods indicate the presence of more than one fault [100]. Such a measurement requires more investigations to diagnose the fault. To illustrate changes of fault gas, both diagnosing methods and authors' observations on fault matching have been summarized in Table V-5.

Table V-5: Fault diagnosis details for Duval triangle and Duval pentagon

Sample	Fault Diagnosis by Duval Pentagon		Fault Diagnosis by Duval Triangle		Fault Matching
	Code	Fault	Code	Fault	
MOF BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
MOB BDV	D2	Electrical discharges of high energy	D2	Electrical discharges of low energy	Matched
MOF PDS	S	Stray gassing	T1	Thermal fault of less than 300 ˚C	Not matched
MOB PDS	S	Stray gassing	T1	Thermal fault of less than 300 ˚C	Not matched
MOF HS	T2	Thermal faults between 300 and 700˚C	T2	Thermal faults between 300 and 700˚C	Matched
MOB HS	T2	Thermal faults between 300 and 700 ˚C	T3	Thermal fault of less than 300 ˚C	Partially matched (Thermal)
NEF BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
NEB BDV	D1	Electrical discharges of low energy	D1	Electrical discharges of low energy	Matched
NEF PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Not matched
NEB PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Not matched
NEF HS	T1	Thermal fault of less than 300 ˚C	T1	Thermal fault of less than 300 ˚C	Matched
NEB HS	T1	Thermal fault of less than 300 ˚C	T1	Thermal fault of less than 300 ˚C	Matched
SEF BDV	D2	Electrical discharges of high energy	D1	Electrical discharges of low energy	Partially Matched (electrical)
SEB BDV	D2	Electrical discharges of high energy	DT	Mixture of electrical and thermal faults	Partially matched (electrical)
SEF PDS	S	Stray gassing	T1	Thermal fault of less than 300 ˚C	Not matched
SEB PDS	S	Stray gassing	DT	Mixture of electrical and thermal faults	Partially matched (Thermal)
SEF HS	S	Stray gassing	T2	Thermal faults between 300 and 700˚C	Not matched
SEB HS	T1	Thermal fault of less than 300 ˚C	T1	Thermal fault of less than 300 ˚C	Matched

It is to be noticed that there is a high disagreement between all partial discharge fault samples for all the dielectric fluids. It is to be recalled that in the present study, a spark is discharged on the surface of the liquid applying 9 kV voltage for five hours. The stray gassing is noticed for fresh dielectric fluids in case of partial discharging activity of the present study. One may understand that even minor partial discharging activities with low energy and for short durations will lead to stray gassing and involves in local temperature raise. To further comment on this, a detailed study on the type of fault diagnosis for partial discharges with different energy levels and different types (surface discharge, internal discharge, and corona discharge) is required. For arcing faults, the fault diagnosis matched almost all the times for fresh samples and aged samples (mineral oil, and ester fluids). However, aged synthetic ester does not match but the similarity may be accepted as they are electrical discharge faults with different intensities. This is due to the aging impact; it is to be recalled that cellulose decay particles have been manually added to get the required acidity values. It is known that; the degradation of cellulose is much higher in mineral oils as compared to ester fluids. Hence, these decay particles added to the oil, differently influence the oil with arcing when compared to the ester fluids. Thermal fault (Hotspot) simulation faults almost matched or partially matched for all samples. However, partial discharges does not match except a partial match for synthetic ester. Fresh natural ester provides the best match between the triangle and the pentagon techniques.

It is to be mentioned that care is taken during the experimentation to avoid interaction of the liquid with external air. Albeit all the three setups are hermetically sealed, a neck headspace is allowed in the test cells. This neck headspace is facilitated for the safety purposes, oil expansion, and to easily accommodate the bubble pressure created. Thus, there is a scope for the fault gases to escape in the gas phase too. The above results are inclusion of only the fault gas that is dissolved in the liquid phase. To understand the gases in the gas phase, Ostwald solubility coefficient of different gases presented in IEEE Std C57.104 are used. The details of the Ostwald coefficients, gas phase gasses, liquid phase gases, and total gas generation is presented in the Table V-6.

Table V-6: Details of total gas generation at different fault conditions in various liquids

Gas		Ostwald coef. (L)	Dissolved gas in liquid phase (ppm)						Dissolved gas in gas phase (ppm)						Total gas generated (ppm)					
			MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB
H_2	BDV	0.0429	125	299	10	195	445	595	2914	6970	233	4545	10373	13869	3039	7269	243	4740	10818	14464
O_2		0.138	24745	2903	24315	5200	827	555	179312	21036	176196	37681	5993	4022	204057	23939	200511	42881	6820	4577
N_2		0.0745	59181	71966	52583	53000	63300	52600	794376	965987	705812	711409	849664	706040	853557	1037953	758395	764409	912964	758640
CO		0.9	10	1083	34	1490	68	236	11	1203	38	1656	76	262	21	2286	72	3146	144	498
CO_2		0.102	558	3176	1243	5320	1060	1950	5471	31137	12186	52157	10392	19118	6029	34313	13429	57477	11452	21068
CH_4		0.337	31	319	192	983	13	19	92	947	570	2917	39	56	123	1266	762	3900	52	75
C_2H_4		1.35	68	1446	19	1540	45	61	50	1071	14	1141	33	45	118	2517	33	2681	78	106
C_2H_6		1.99	4	125	1	198	62	14	2	63	1	99	31	7	6	188	2	297	93	21
C_2H_2		0.938	492	1113	192	983	324	471	525	1187	205	1048	345	502	1017	2300	397	2031	669	973

Gas		Ostwald coef. (L)	Dissolved gas in liquid phase (units)						Dissolved gas in gas phase (units)						Total gas generated (units)					
			MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB
H_2	PDS	0.0429	1910	1527	1330	1390	1220	1140	44522	35594	31002	32401	28438	26573	46432	37121	32332	33791	29658	27713
O_2		0.138	100	13358	19200	10400	1060	329	725	96797	139130	75362	7681	2384	825	110155	158330	85762	8741	2713
N_2		0.0745	13782	91947	55100	51500	8770	23100	184993	1234188	739597	691275	117718	310067	198775	1326135	794697	742775	126488	333167
CO		0.9	459	649	992	1280	907	760	510	721	1102	1422	1008	844	969	1370	2094	2702	1915	1604
CO_2		0.102	4114	6724	8840	16100	6660	4810	40333	65922	86667	157843	65294	47157	44447	72646	95507	173943	71954	51967
CH_4		0.337	1004	1018	1080	1520	397	359	2979	3021	3205	4510	1178	1065	3983	4039	4285	6030	1575	1424
C_2H_4		1.35	10	11	3	6	23	16	7	8	2	4	17	12	17	19	5	10	40	28
C_2H_6		1.99	100	100	145	235	215	67	50	50	73	118	108	34	150	150	218	353	323	101
C_2H_2		0.938	16	23	24	27	61	48	17	25	26	29	65	51	33	48	50	56	126	99

Gas		Ostwald coef. (L)	Dissolved gas in liquid phase (units)						Dissolved gas in gas phase (units)						Total gas generated (units)					
			MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB	MOF	MOB	SEF	SEB	NEF	NEB
H_2	HS	0.0429	37	225	49	48	60	150	862	5245	1142	1119	1399	3497	899	5470	1191	1167	1459	3647
O_2		0.138	5932	650	12943	9140	655	606	42986	4710	93790	66232	4746	4391	48918	5360	106733	75372	5401	4997
N_2		0.0745	73200	75032	67623	60869	54100	53400	982550	1007141	907691	817034	726174	716779	1055750	1082173	975314	877903	780274	770179
CO		0.9	1375	1600	2100	4112	465	783	1528	1778	2333	4569	517	870	2903	3378	4433	8681	982	1653
CO_2		0.102	2053	2141	4601	9566	1870	2340	20127	20990	45108	93784	18333	22941	22180	23131	49709	103350	20203	25281
CH_4		0.337	404	1333	424	851	24	36	1199	3955	1258	2525	71	107	1603	5288	1682	3376	95	143
C_2H_4		1.35	120	1471	284	755	11	15	89	1090	210	559	8	11	209	2561	494	1314	19	26
C_2H_6		1.99	97	1259	1154	1773	1020	1930	49	633	580	891	513	970	146	1892	1734	2664	1533	2900
C_2H_2		0.938	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2

It is to be mentioned that the details of Ostwald solubility coefficients in case of ester fluids are not yet reported in IEEE Std C57.155. Therefore, for illustration purposes the coefficients reported in IEEE Std C57.104 have been used in the present study. The details of the accuracy and repeatability of individual gases measurements are provided in Table V-7.

Table V-7: Accuracy and repeatability details of the individual gases

Gas	Accuracy	Repeatability
H_2	±0.5 ppm or ±5%	±0.5 ppm or ±3%
O_2	±500 ppm or ±15%	±500 ppm or ±10%
N_2	±2.000 ppm or ±15%	±2.000 ppm or ±10%
CO	±10 ppm or ±5%	±10 ppm or ±3%
CO_2	±15 ppm or ±5%	±15 ppm or ±3%
CH_4	±0.2 ppm or ±5%	±0.5 ppm or ±3%
C_2H_2	±0.2 ppm or ±5%	±0.5 ppm or ±3%
C_2H_4	±0.2 ppm or ±5%	±0.5 ppm or ±3%
C_2H_6	±0.2 ppm or ±6%	±0.5 ppm or ±4%

5.5 CONCLUSION

The influence of the condition of the dielectric fluid on gassing has been reported for mineral oil, natural and synthetic esters under electrical and thermal faults. The degradation under fault conditions has been reported using dissolved decay contents, absorbance and turbidity. The dissolved gas analysis by the application of Duval fault gas diagnostic methods are adopted to understand the gassing behaviour of the dielectric fluids. It is inferred that fault gases in a transformer evolve with respect to degradation of the dielectric fluid. As degradation of the fluid is highly dynamic with operating times, there is a need to understand the gassing tendency of an insulation liquid vis-à-vis aging markers. It is also found that the concentration and type of dissolved gases generated depend on the type of fault. In other words, the gassing tendency and fault gases will not be the same for a similar type of fault at different fault durations and fault energy. The theoretical premise that aging byproducts affects the gassing tendency and DGA is experimentally confirmed. The results reported in this study should be helpful in further improving the dissolved gas analysis of ester filed transformers. Dissolved gas analysis is a potential fault diagnosing tool having a large variance in the research results reported by various researchers across the globe. Thus, it is necessary to focus on research on the dissolved gas analysis of alternative dielectric fluids at different aging conditions, different fault intensities and fault durations.

Chapter VI

MONITORING COLLOIDAL AND DISSOLVED DECAY PARTICLES IN ESTER DIELECTRICS FLUIDS

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Monitoring Colloidal and Dissolved Decay Particles in Ester Dielectrics Fluids

Résumé

Dans cet article, deux esters synthétiques ainsi qu'un ester naturel sont étudiés pour surveiller la génération de particules colloïdales et de désintégration dissoutes sous vieillissement thermique. Le vieillissement thermique des fluides est réalisé selon une norme ASTM D1934 modifiée en présence de cellulose et de cuivre à des températures élevées. Par la suite, les particules colloïdales et de désintégration dissoutes sont contrôlées conformément aux normes ASTM D1698 (traitement par centrifugation) et ASTM D7150 (régénération par terre de Foulon), respectivement. Les liquides diélectriques vieillis et traités sont caractérisés pour le nombre de particules dissoutes, les courbes d'absorbance, la concentration de la teneur de particules dissoutes et la turbidité selon les normes ASTM. L'évolution des teneurs en particules colloïdales et de désintégration dissoutes est rapportée individuellement pour les fluides esters et l'huile minérale. La dégradation de l'huile minérale a été observée à la fois par des particules dissoutes et colloïdales. La génération de particules colloïdales suite à la dégradation des fluides esters est presque négligeable, tandis que la teneur du contenu de produits de dégradation dissous est observée avec la dégradation thermique dans le temps. Il est important de noter que les résultats obtenus montrent la capacité des esters à dissoudre plus de boue que l'huile minérale. Ceci est dû à la stabilité élevée (à l'oxydation) de l'ester conduisant à des produits de décomposition radicalaire réduits. De plus, la nature solvant en température du groupe ester a tendance à dissoudre les particules de boue de nouveau à la phase liquide dans le liquide en vrac.

Abstract

In this article, two synthetic esters along with a natural ester are investigated to monitor the generation of colloidal and dissolved decay particles under thermal aging. The thermal aging of the fluids is carried out as per a modified ASTM D1934 in the presence of cellulose and copper at elevated temperatures. Later, the colloidal and dissolved decay particles are monitored as per ASTM D1698 (centrifuge treatment) and ASTM D7150 (Fuller's earth reclamation), respectively. The aged and treated dielectric liquids are characterized for the number of decay particles, oil absorbance curves, the concentration of dissolved decay content, and turbidity as per ASTM standards. The evolution of colloidal and dissolved decay contents is individually reported for ester fluids and mineral oil. The degradation in mineral oil has been witnessed by both dissolved and colloidal particles. The generation of colloidal particles following the degradation of ester fluids is almost negligible, whereas dissolved decay content is noticed with thermal degradation time. Importantly, the obtained results depict the ability of esters to dissolve more sludge. This is due to the high (oxidative) stability of ester leading to reduced radical decomposition products. Also, the temperature solvent nature of the ester group tends to dissolve sludge particles back to the liquid phase into the bulk liquid.

6.1 INTRODUCTION

Ester dielectric fluids are being well accepted for use in oil-filled apparatus as alternatives to mineral insulating oils [30] [33] [43]. The degradation aspects of ester fluids in comparison to mineral oils were investigated by several researchers and the details of which are summarized in the literature [30] [64]. In transformers, copper catalysts, aging byproducts, loading cycles, vibrations, electrical stress, etc. accelerate the degradation of a dielectric liquid. During the aging process, sludge, moisture, acids, and gases are formed [162]. The build-up of acids precedes the formation of sludge in the transformer, which is the end product of the oxidation process. Statistically, these species appear when the insulating liquid is degraded enough for promoting the aggregation of these particles together (colloids).

Peroxides are primary oxidation compounds in insulating liquids, and all the secondary oxidation compounds (volatile, non-volatile, high molecular weight, and free fatty acid) derive from hydroperoxide decomposition [146]. Before colloids appear, the first sign will be the drop in the interfacial tension (IFT) accompanied by an increase of the total acid number (TAN) and dissolved decay products (DDP) [163] [164] [28] [14]. It is to be mentioned that the acid number of the ester fluids is higher than mineral oils as esters are synthesized from fatty acids. Therefore, the detrimental levels of acid number and interfacial tension are different for mineral oils and ester fluids. The TAN, which is used to reflect the oxidation performance of mineral oils, may not be suitable for vegetable oils [164]. This is because not only oxidation but also hydrolysis of vegetable oils generate acids. Therefore, in the present work to study the colloidal and dissolved particles with aging, particle counter, concentration of dissolved decay products, oil absorbance curves, and turbidity measurements are adopted as monitoring parameters.

The degradation of oil-paper insulation is evident by the production of decay products that may or may not be dissolved in the insulating liquid. The dissolved decay particles are generally minute in size and are found soluble/dissolved in the insulation oil. Similarly, colloidal decay products are of different sizes and are distributed within the bulk oil in the transformer. Colloidal and dissolved particles act as local conducting elements in the oil and adversely affect the physicochemical and dielectric properties of the insulation oil [165]. As per CIGRE 157 (technical brochure), large portion of the transformer failures is observed due to defects in the insulation system where decay particles have much contribution towards the transformer insulation system failure [165]. To understand decay particles, ASTM developed a standard test method (ASTM D D6786-08) to estimate the number of particles in the insulating fluid and quantify the particle size (diameter). There is significantly less literature on the treatment (reclamation/regeneration) of these new insulating fluids and monitoring sludge in esters[166] [167].

In this work, efforts are made to understand the colloidal and dissolved decay products in natural ester and synthetic ester in comparison to mineral insulating oil. The evaluation of colloidal and dissolved particles is understood by treating the aged oils using two different methods. Centrifuge method as per ASTM D1698 and Fuller’s earth reclamation as per ASTM D7150 are used to study the colloidal and dissolved particles, respectively. To emphasize and illustrate the influence of both methods, the results of the centrifugal method and Fuller's earth reclamation have been discussed in two different sections. It is found that degradation of ester fluids has witnessed only tiny and dissolved particles, whereas mineral oil degradation is involved with colloidal and dissolved decay particles.

6.2 REVIEW OF THE INFLUENCE OF COLLOIDAL AND DISSOLVED PARTICLES

Generally, cellulose fibers and metallic particles contribute to the decay particles in the transformer. The presence of metallic particles is a higher indication of damage to the insulation system than that of the cellulose fibers [165]. The geometry (shape and size) of these particles play a critical role in deciding the degree of oil contamination and vulnerability. The size of the decay products introduced to the oil may vary from few microns to hundreds of microns. The distribution of the decay particles size is as follows: Tiny particles: Less than 25 microns (a few thousand). Small particles: In the range of 25-100 microns (a few hundred). High-grade particles: Over 100 microns (very less). The details of the colloidal and dissolved particles in a transformer insulating oil are summarized in Figure VI-1.

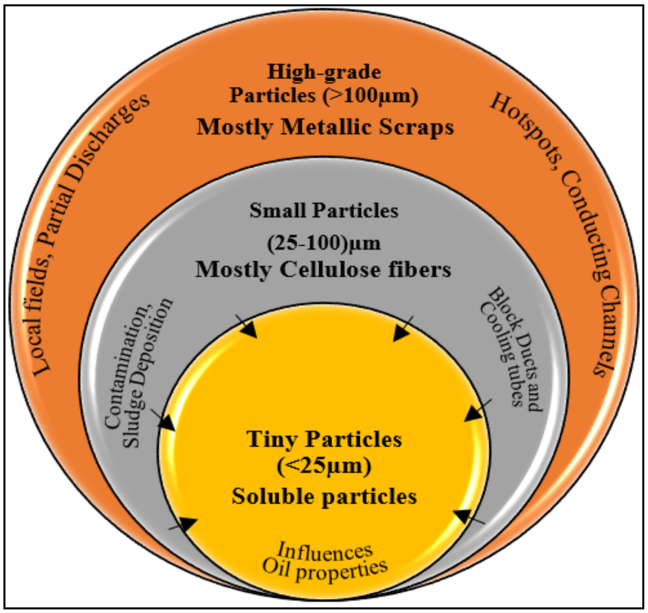


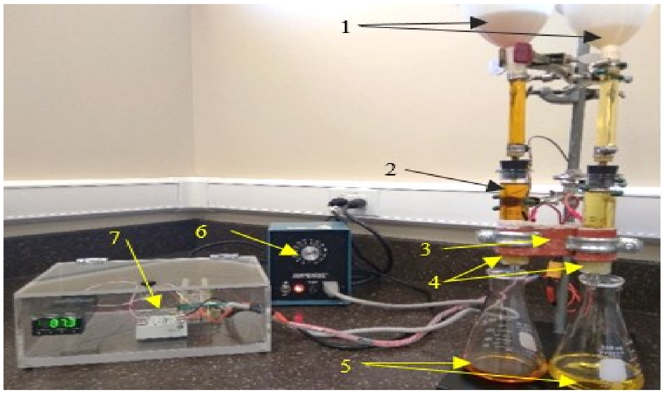
Figure VI-1: Illustration of decay particles and their influence on transformer insulation oil sketched in accordance with CIGRE brochure 157 [165].

However, some metallic particles that wear out of core-winding assembly and rubber scraps from gaskets/sealing maybe even bigger in size. The shape of these particles is not definite and is highly irregular with rough surfaces at the micro-level [168]. The presence of these particles in the insulating fluid adversely affects the performance of the transformer and properties of the dielectric fluid. The phenomenal effects of colloidal and dissolved particles evolved in the insulating fluids with aging depend on their size.

The tiny particles (<25 microns) are almost dissolved in the oil and affect the dielectric and physicochemical properties of the oil. The presence of these dissolved decay particles majorly influences properties like dielectric strength, acidity, interfacial tension, and colour. Small particles (25-100 microns) aid to the effect of tiny particles and lead to oil contamination, blocking of ducts, hampering the oil flow through cooling tubes, and sludge depositions. It is to be mentioned that majority of the small particles contribute to the decay contents that are aroused due to the degradation of the solid insulation system. These particles are almost colloidal particles that may be dissolved with operating times due to high temperatures. These particles may not be directly dissolved with operating times, but they may further split into multiple particles known as sister particles. These sister particles may also further split into multiple particles, and this process continues with time. This splitting process is mainly attributable to the operating time, internal temperature, and pressure that act in a physical reduction of particle size. There is a high probability for the size of the sister particles to fall less than <25 microns and dissolve with operating time. High-grade particles (>100 microns) further intensify the consequences of particles that are less than 100 microns. High-grade particles act as conductive particles and initiate local electrical stress. This weakens the overall insulation integrity by initiating local partial discharges, conducting channels, and hotspots [168]. The majority of the high-grade particles are metallic particles, rubber scraps, and cellulose scraps.

6.3 EXPERIMENTAL SET-UP

Even though transformer oil-paper insulation aging is the result of a combination of factors, the life of oil-paper insulation is actually determined mainly by its thermal degradation, which is the most important element in many aging factors [164]. For the present study, unused mineral oil (MO), synthetic ester A (SEA), synthetic ester B (SEB), and natural ester (NE) have been subjected to thermal aging as per modified ASTM D1934 standard procedure in the presence of cellulose and copper. Cellulose insulants include kraft paper and pressboard together, contributing to a 1:10 ratio with the insulation oil. Thermal aging is carried such that aging history of the oil/paper insulation is retained at 115 °C, 150 °C, 175 °C, and 195 °C for two weeks each, which totals to 8 weeks of aging. The thermal aging process followed a consecutive heating and cooling (to room temperature) cycles for 12 hours each throughout the aging process. Only heating duration has been considered as the aging period. The heating and cooling cycles are adopted to simulate potential moisture migrations and subsequent degradation. In addition, heating and cooling cycles allow simulating variable thermal excursion on the oil/paper insulation, which induce an aggressive aging mechanism. Even though natural esters are 'not recommended' for breathing transformers due to their lower oxidation stability, all the fluid samples were submitted to open beaker oxidative thermal with the aim of comparative oxidation stability. While the oxidative thermal aging procedure is not representative of a real transformer, it has the advantage of being rapid and providing samples with a controlled thermal history [164] [169] [170]. Aged oils are subjected to diagnostic characterizations that include turbidity (ASTM D6181), particle count (ASTM D6786), Ultraviolet-Visible infrared spectroscopy (ASTM D6802). Further, aged oils are subjected to centrifuge as per ASTM D1698 and Fuller's earth reclamation as per ASTM D7150 to separate colloidal and dissolved particles, respectively. Fuller's earth reclamation, a laboratory setup was developed as shown in Figure VI-2. For centrifugal treatment, a typical centrifuge instrument is used and it is shown in Figure VI-3. The Flowchart of the experimental study is Figure VI-4.



1. Oil Samples
2. Oil in filtering units
3. Heating element
4. Fullers earth
5. Filtered oil
6. Variac
7. Temperature controller unit

Figure VI-2: Laboratory setup used for Fuller's earth reclamation

Figure VI-3: Laboratory setup used for centrifugal treatment.

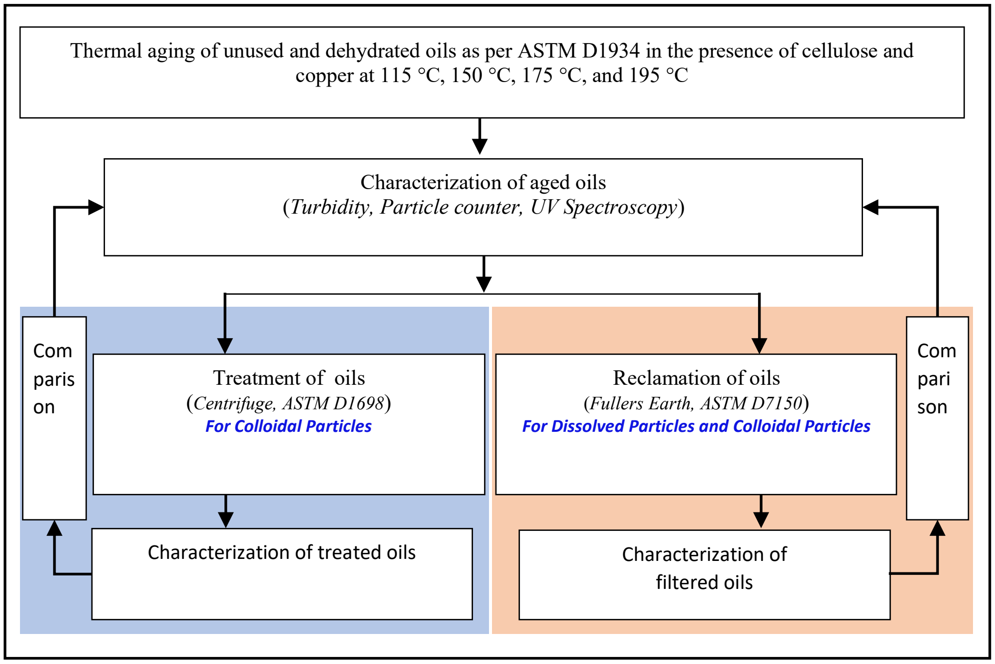


Figure VI-4: Flowchart of the experimental study.

Both centrifuge-treated and Fuller's earth filtered oils have been tested for turbidity, particle count, and Ultraviolet Visible (UV) infrared spectroscopy. It is to be mentioned that filtering is carried out at a preheat temperature of 80 °C with 1 g of clay to 30 ml of oil for a single pass. The properties of the alternative dielectric fluids considered for this study are summarized in Table VI-1.

Table VI-1: Properties of the base fluids

Property	NE	SEA	SEB	MO
Density (kg/m^3) @20 °C, ASTM D1298	0.92	0.97	0.97	0.869
Viscosity (cSt) @40 °C ISO 3104	32	29	31	9.2
Water content (ppm), IEC 60814)	50	50	<90	<20
Dissipation factor, IEC 60247	<0.03	<0.03	0.02	< 0.001
Breakdown voltage (kV), IEC 60156	>75	>75	>60	>70
Acidity (mg KOH/kg), IEC 62021	< 0.04	< 0.03	0.01	< 0.01
Flash point (°C), ISO 2719	>260	260	>250	148
Pour Point (°C), ISO 3016	-18	-56	<-45	-54
Absorbance (Abs), ASTM D6802	0.105	0.012	0.036	4.62
Turbidity (NTU), ASTM D6181	0.381	0.289	0.133	0.14

6.4 RESULTS AND DISCUSSIONS

6.4.1 IMPACT OF COLLOIDAL PARTICLES (CENTRIGFUGAL TREATMENT)

The presence of aging byproducts greatly influences the absorbance of the oil. Thus, UV spectral curves are displaced based on the concentration of these decay particles. The colloidal particles are collected using centrifuging forces. Hence, theoretically speaking, the absorbance of the oil to light changes and tends to shift the curve to lower wavelengths. The spectral curves of the aged MO, NE, SEA, SEB, and centrifuged MO are shown in Figure VI-5 to Figure VI-8 for different aging factors. It is to be noticed that there are no colloidal particles noticed in mineral oil at 115 °C, and hence centrifuged MO curve is overlapped with MO (aged 115 °C for two weeks) oil in Figure VI-5.

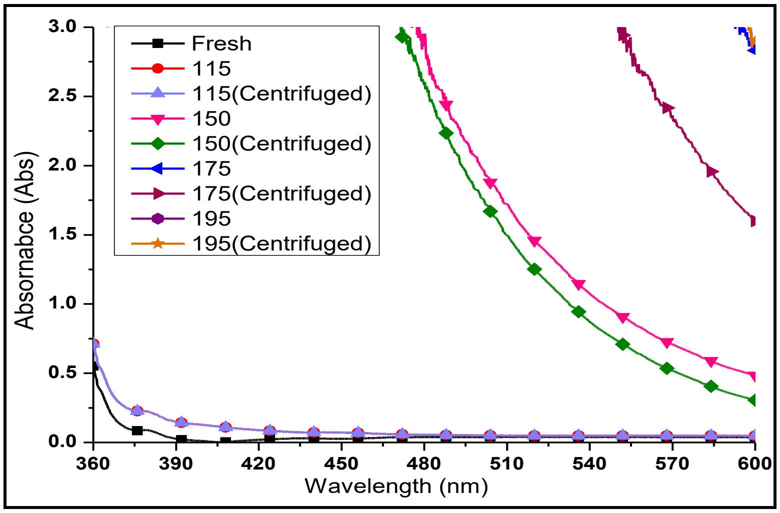


Figure VI-5: UV/Vis spectral curves for various oils at different aging temperatures (°C) for Mineral Oil.

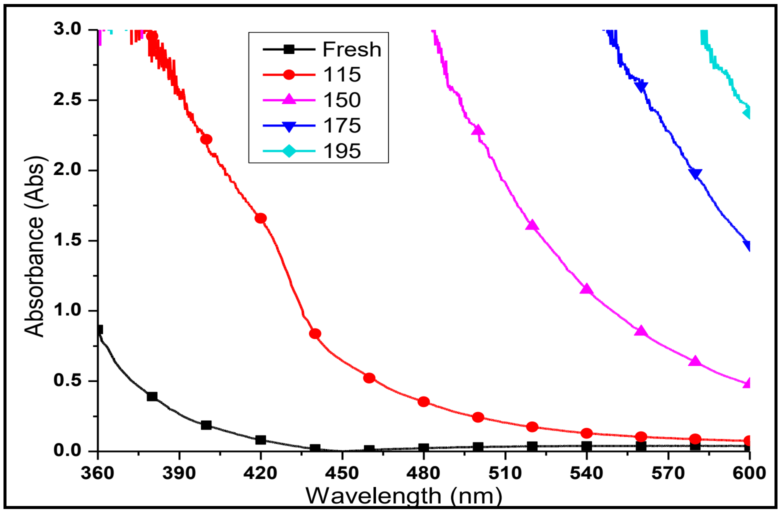


Figure VI-6: UV/Vis spectral curves for various oils at different aging temperatures (°C) for Natural Ester.

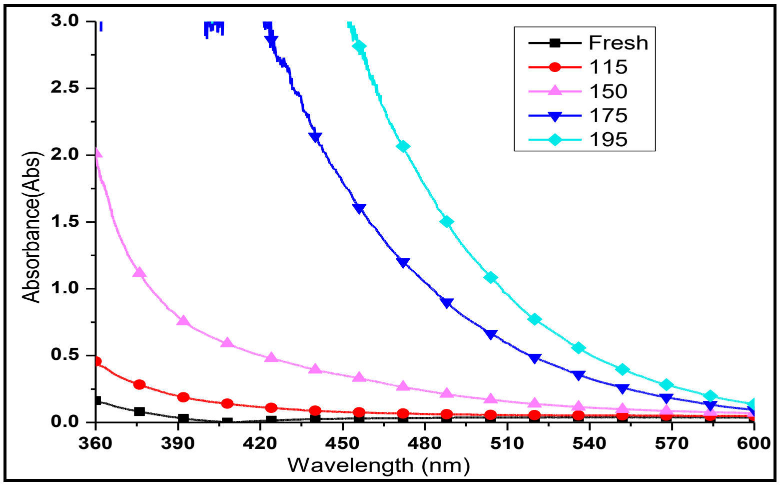


Figure VI-7: UV/Vis spectral curves for various oils at different aging temperatures (°C) for Synthetic Ester A.

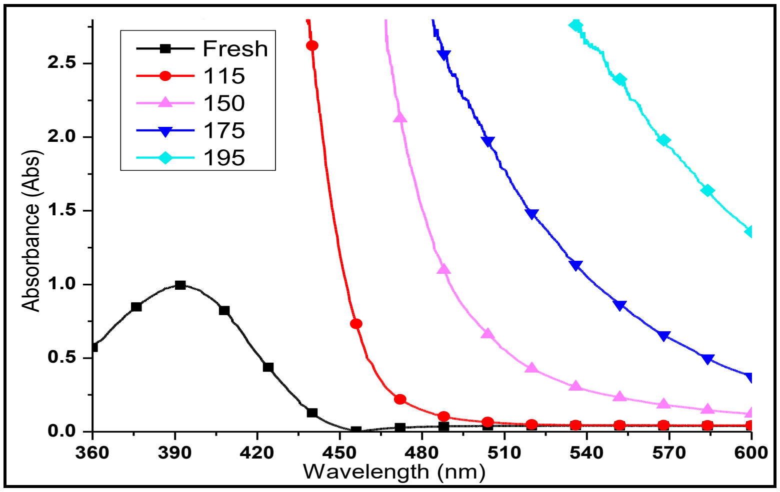


Figure VI-8: UV/Vis spectral curves for various oils at different aging temperatures (°C) for Synthetic ester B.

It is observed that colloidal particles are not generated in natural ester and synthetic ester (SEA and SEB) with aging times. It is to be mentioned that the centrifuging activity for ester fluids revealed no evidence of the colloidal particles. However, the change in absorbance of the ester fluids (NE, SEA, and SEB) in Figure VI-6, Figure VI-7, and Figure VI-8 is due to the dissolved decay contents (non- colloidal particles or tiny particles that are not separable through centrifuge activity) that are produced with aging. However, the same are evolved significantly in mineral insulation oils for 150 °C, 175 °C, and 195 °C aging factors. The difference in aged MO and centrifuged MO is clearly seen in Figure VI-5. Also, in Figure VI-5 mineral oil is significantly degraded and is shifted to higher wavelengths of spectral curves. This limit may be explained by the wavelength limits (360-600 nm) of ASTM D6802.

The average absorbance of various oils is presented in Figure VI-9. To avoid a direct comparison of mineral oil and ester fluids, a dual-axis is adopted. It is seen that the absorbance of aged mineral oil is increasing with aging when compared to the centrifuged mineral oil. In addition, at higher aging temperatures, the absorbance of ester fluids is even better than that of the treated mineral oil.

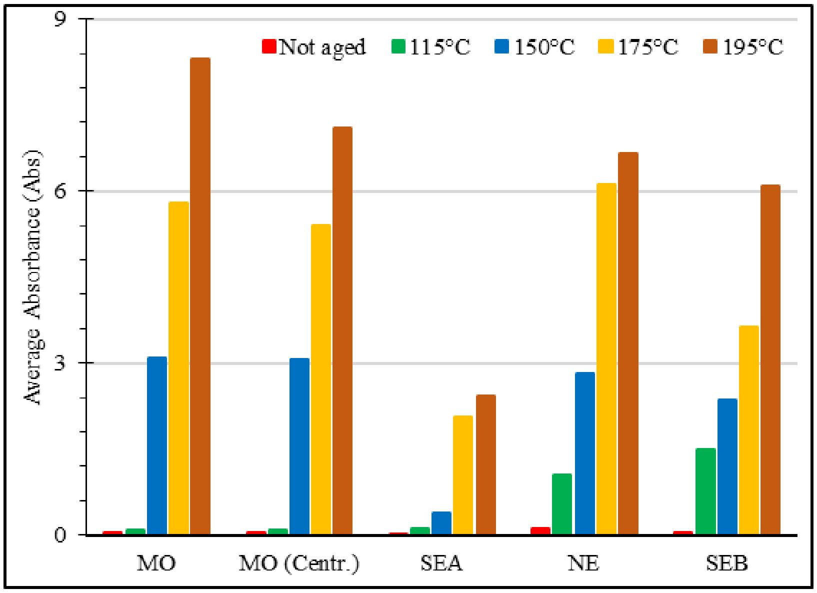


Figure VI-9: Average absorbance from (360-600) nm wavelength of different oils as a function of thermal aging.

The turbidity of the insulating oil gives information on the transparency nature i.e., the degree to which oil is clear without impurities or suspended particles in it. It is known that turbidity of oil increases with an increase in thermal age, and the same can be brought down with the removal of suspended and colloidal particles [39]. The changes in turbidity of MO, NE, SEA, SEB, and centrifuged MO is presented in Figure VI-10.

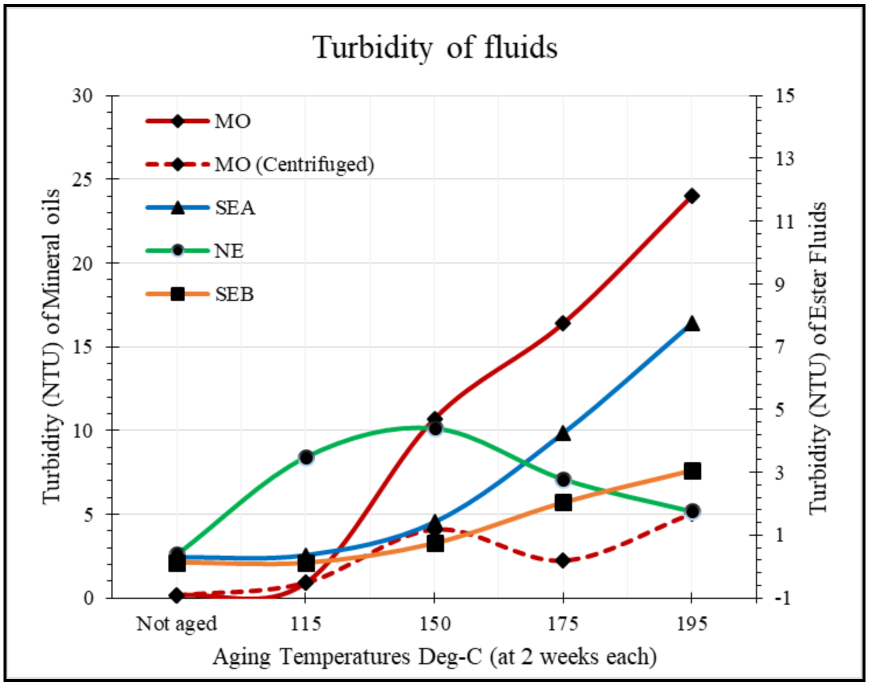


Figure VI-10: Turbidity of different oil as a function of thermal aging.

The turbidity of mineral oil increased rapidly with thermal aging, while the increase in turbidity of ester fluids is seen to be low. It is also observed that turbidity of centrifuged mineral oil is comparable to the turbidity of ester fluids. This increase in turbidity of centrifuged MO is attributable to the tiny and dissolved decay particles that are present in the oil. Because through centrifuge activity, only colloidal particles have been removed. The presence of other decay particles (non- colloidal particles or tiny particles that are not separable through centrifuge activity) still affects the turbidity.

Some minor and tiny particles are not separable by the centrifuge. This is because these particles may be almost similar to the dissolved particles. The details of the particle count for MO, NE, SEA, SEB, and centrifuged MO are shown in Figure VI-11 to Figure VI-14. From Figure VI-11, it is noticed that the number of larger diameter particles reduced with centrifuge treatment. This is due to the separation of colloidal particles through centrifuge treatment. This reduction in the number of particles affected the light absorbance of the oil and hence shifted the absorbance curve to the lower wavelengths with the removal of colloidal particles, as seen in Figure VI-10.

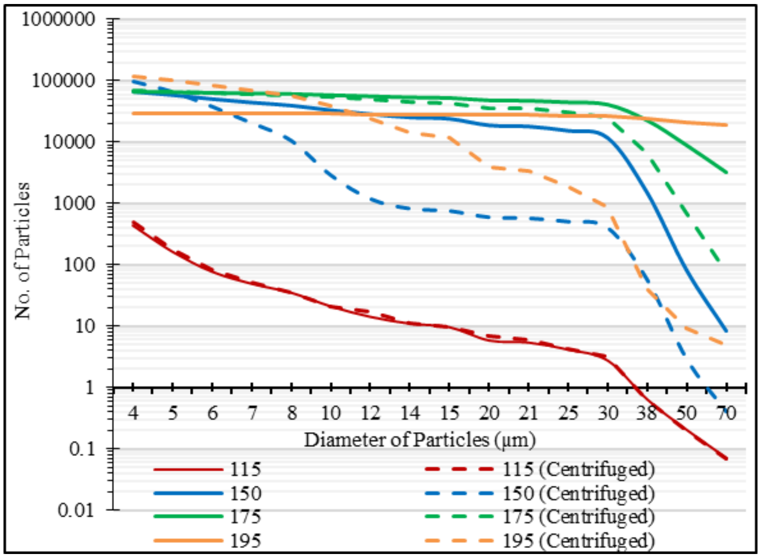


Figure VI-11: Particle count as a function of diameter for mineral oil at different aging temperatures (°C).

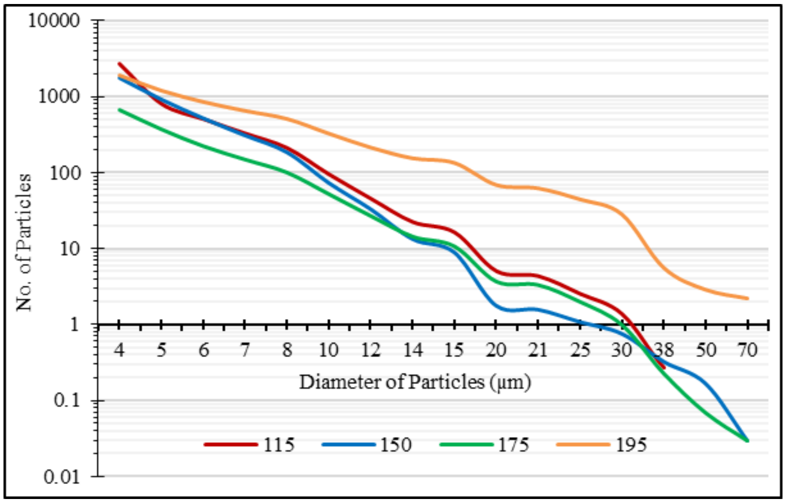


Figure VI-12: Particle count as a function of diameter for natural ester at different aging temperatures (°C).

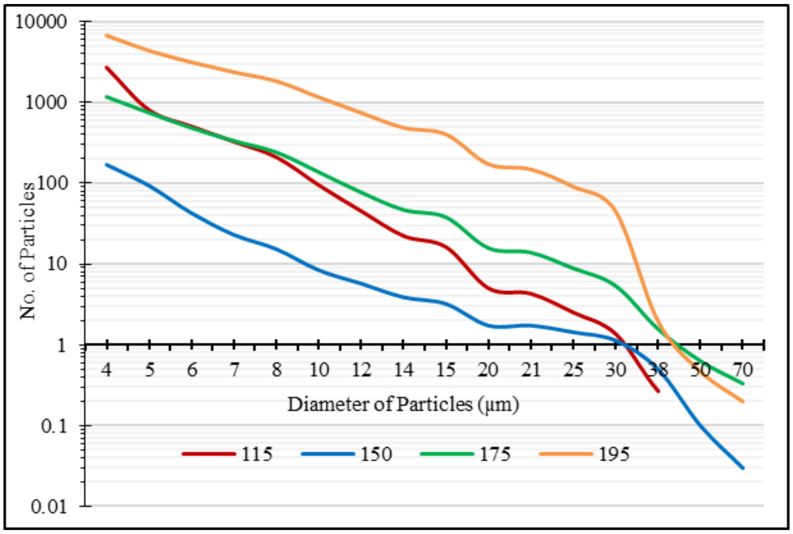


Figure VI-13: Particle count as a function of diameter for synthetic ester A at different aging temperatures (°C).

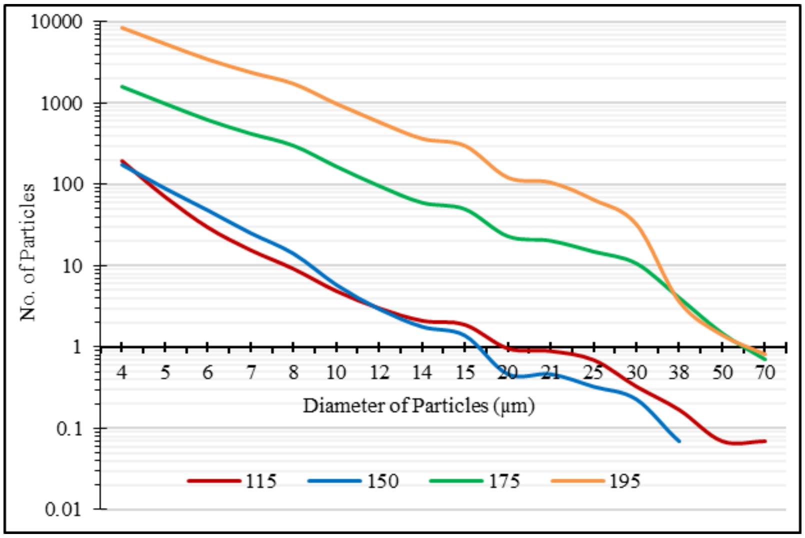


Figure VI-14: Particle count as a function of diameter for synthetic ester B at different aging temperatures.

Also, particles having smaller diameters are noticed to increase slightly after the centrifugal process. This is because some colloidal particles may split into small particles due to high mechanical forces during the centrifuge treatment. Even though these particles are reduced to a certain extent with centrifugal treatment, the absorbance and the turbidity of ester dielectric fluids and treated mineral oil are comparable. This is due to the presence of smaller diameter colloidal particles in the treated mineral oil.

- Observing MO, NE SEA, and SEB has demonstrated the potential of ester fluids towards withstanding oxidative degradation. This indicates the resistance of ester fluids towards the generation of colloidal particles.

- Looking at SEA, SEB, NE with centrifuged MO indicate a larger number of particles in mineral oil even after treatment. This demonstrates the superiority of ester fluids towards the rate of thermal degradation.

- Observing mineral oil and treated mineral oil in the particle counter section (see Figure VI-11) indicate a crossover in the trending pattern of the number of particles. This is due to the presence of smaller diameter particles in oil after centrifugal treatment.

It is inferred that the generation of colloidal particles following the degradation of ester fluids is almost negligible, whereas the degradation of mineral insulating oil is largely influenced by the colloidal particles. Importantly, the obtained results depict the ability of esters to dissolve more sludge. This is due to the high (oxidative) stability of the ester group, leading to reduced radical decomposition products. In addition, the temperature solvent nature of the ester group tends to dissolve sludge particles back to the liquid phase into the bulk liquid. A similar observation on esters to dissolve more sludge is reported in [171] while subjecting esters to electrical stress.

6.4.2 IMPACT OF DISSOLVED PARTICLES (FULLER'S EARTH RECLAMATION)

It is to be understood that this filtering is intended to avoid colloidal and dissolved particles from the degraded oil. The impact of colloidal particles alone is presented in the previous section. Hence, the discussions in this section are in the interest of tiny decay particles and other dissolved particles in the oil.

To understand the influence of dissolved decay contents, UV/Vis spectroscopy characterizations are performed after Fuller's earth reclamation. Oil samples are subjected to Fuller's earth reclamation. This treatment acted in removing various aging byproducts, including the tiny particle and dissolved products. Hence, the absorbance curves tend to shift the curve accordingly. The UV spectral curves of various aged oils and filtered oils are presented in Figure VI-15 to Figure VI-18. From these Figures, it is noticed that decay contents are reduced with reclamation.

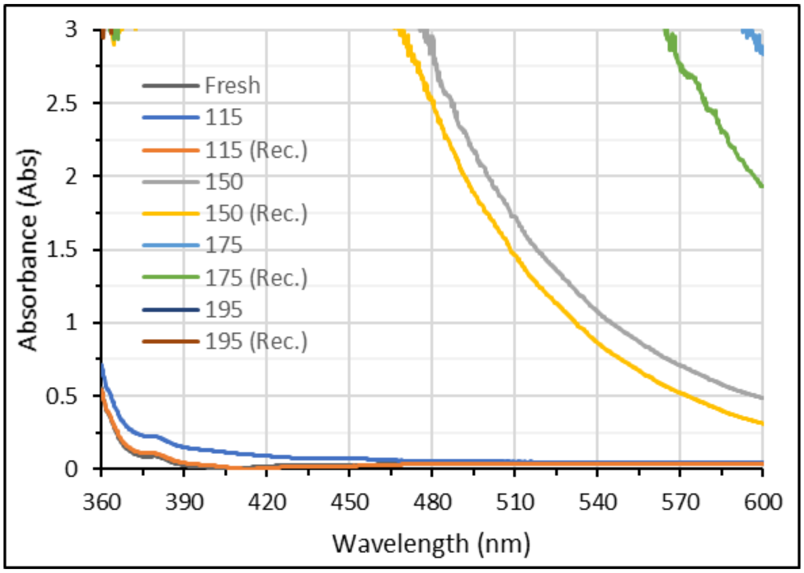


Figure VI-15: UV/Vis spectral curves for mineral oil at different aging temperatures (°C).

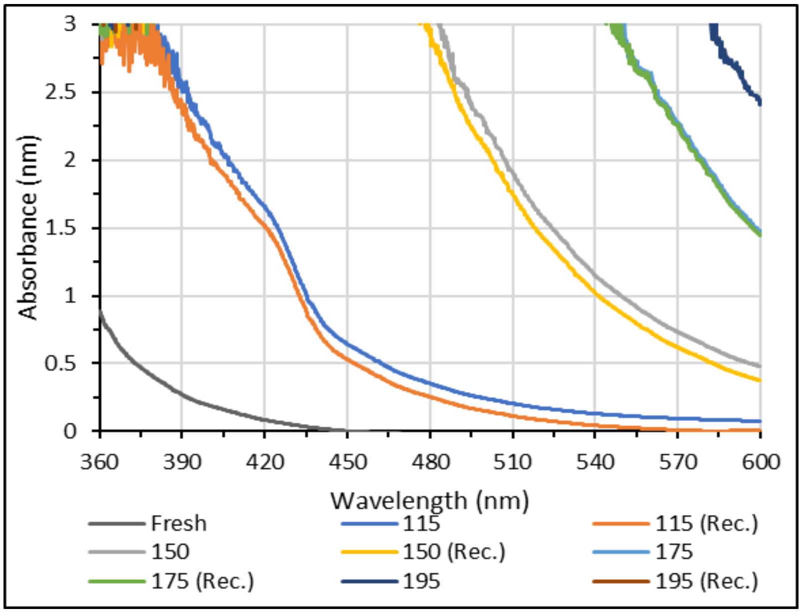


Figure VI-16: UV/Vis spectral curves for natural ester at different aging temperatures (°C).

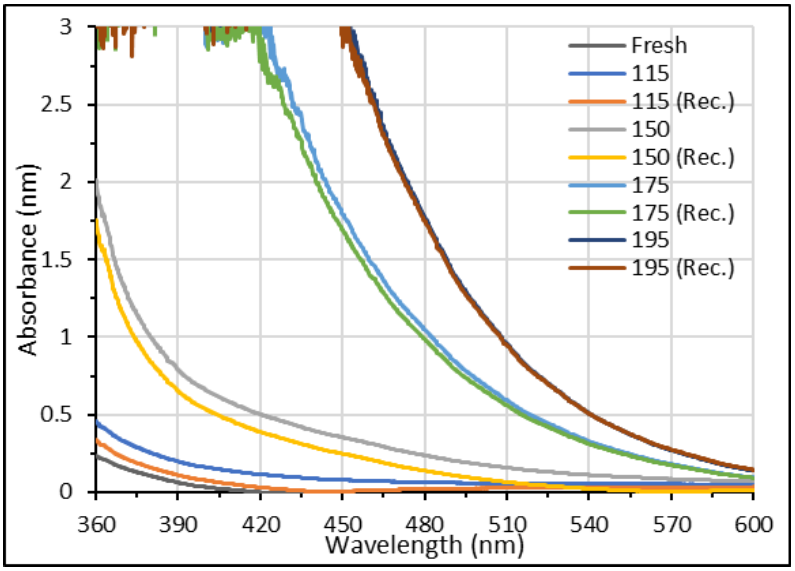


Figure VI-17: UV/Vis spectral curves for synthetic ester A at different aging temperatures (°C).

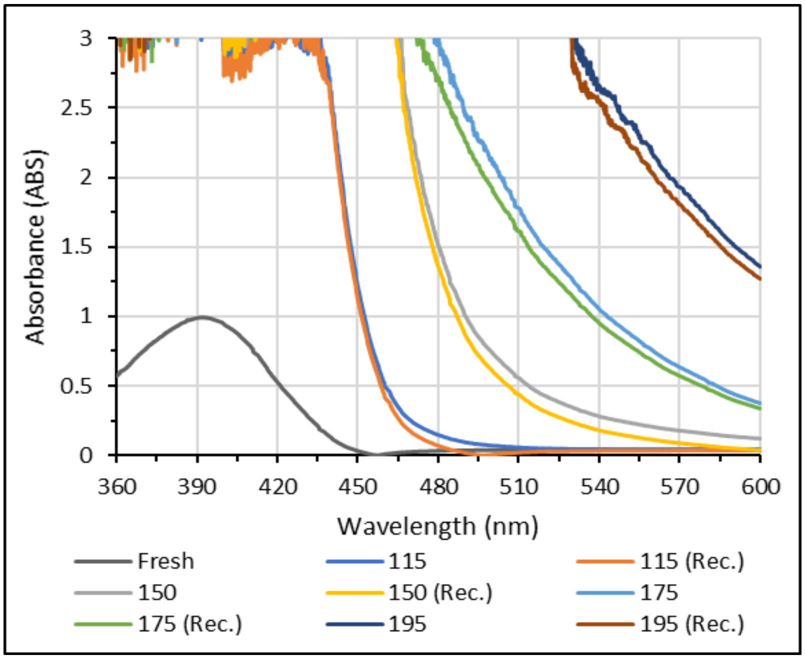


Figure VI-18: UV/Vis spectral curves for synthetic ester B at different aging temperatures (°C).

From Figure VI-15, it is observed that the reduction in decay products with filtering in the case of mineral oil is increasing with the increase in age. The absence of mineral oil corresponding to 195ºC is due to the wavelength limits as per the ASTM D6802. It is to be understood that at such stage of aging, mineral oil is extremely degraded and shifted to higher wavelengths. The change in decay contents with reclamation of ester-based oils is very low when compared to mineral oils. This illustrates the fact that the rate of decay product evaluation is very low in the case of ester dielectric fluids when compared to mineral oils. The details of changes in oil absorbance are as shown in Figure VI-19.

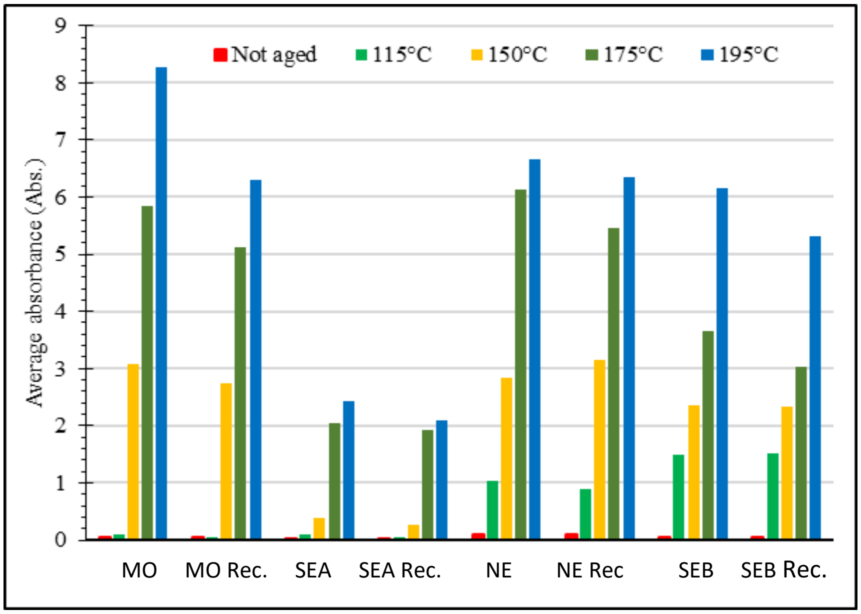


Figure VI-19: Average absorbance from (360-600) nm wavelength of aged and reclaimed oils as a function of thermal aging.

The reduction in absorbance of ester fluids with reclamation is significant after 150 °C. This reduction in absorbance is seen in the early stages of aging in the case of mineral oil. This reveals the early evolution of decay contents in mineral oils as compared to ester fluids. It is to be noted that filtering is performed at 80 °C for a single pass only.

Turbidity of aged and filtered oils have been measured as per ASTM D6181. The change in turbidity for aged and treated oils with aging time is shown in Figure VI-20.

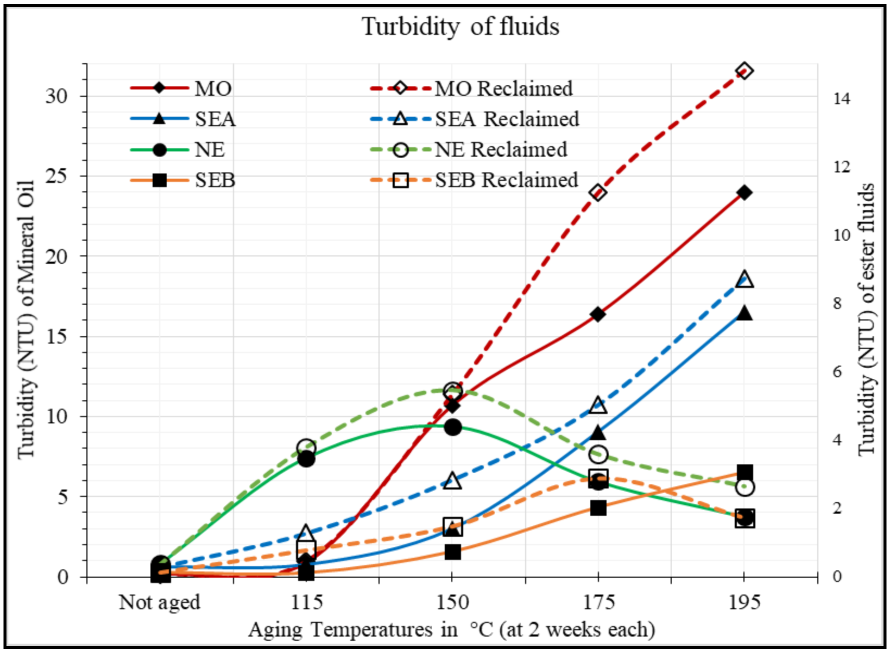


Figure VI-20: Turbidity of aged oils and filtered oils as a function of aging.

It is noticed that the turbidity of ester fluids increased with Fuller's earth reclamation. However, the turbidity of mineral oil remained the same at shorter aging duration and increased at longer aging with reclamation. It is to be mentioned that an appropriate layer of cotton filter is placed at the bottom of the Fuller's earth layer to avoid the transfer of clay particles to the filtered oil. This increase in turbidity may be understood by the particle counter measurements.

Number of particles in oils are measured before and after Fuller's earth reclamation. The details of the number of particles as a function of the particle size for MO, NE, SEA, and SEB at different aging conditions are presented in Figure VI-21 to Figure VI-24. The number of large diameter particles is reduced with reclamation. This removal of larger particles reduced with elapsed aging durations in mineral oil and natural ester, while it is increased with an increase in aging in the case of synthetic esters. These observations are noticed from the crossovers seen on the graphs for filtered and non-filtered oils. For NE, SEA, and SEB, it is also noticed that the quantity of smaller diameter particles are increased with Fuller's earth treatment. This increase could be the possible reason for an increase in the turbidity of filtered oils.

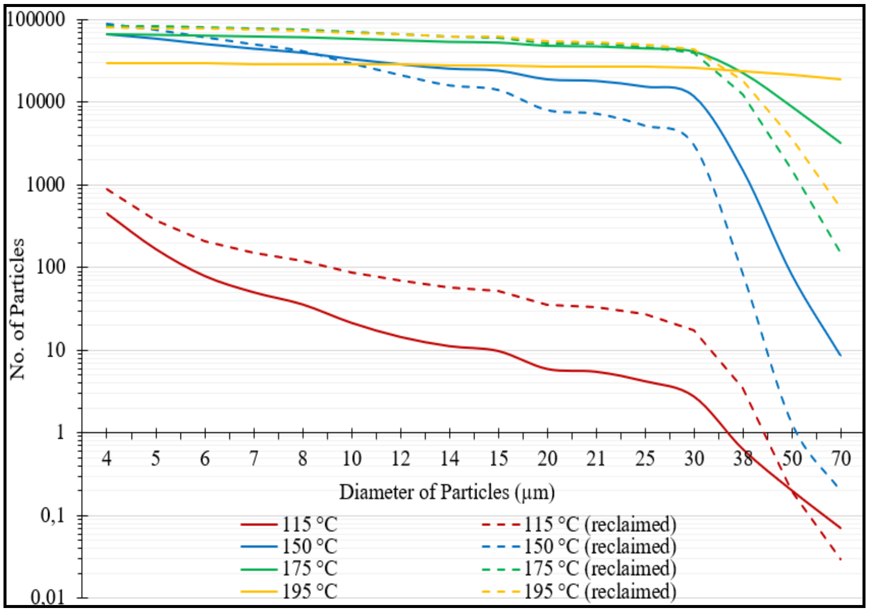


Figure VI-21: Particle count as a function of diameter for mineral oil at different aging temperatures (°C).

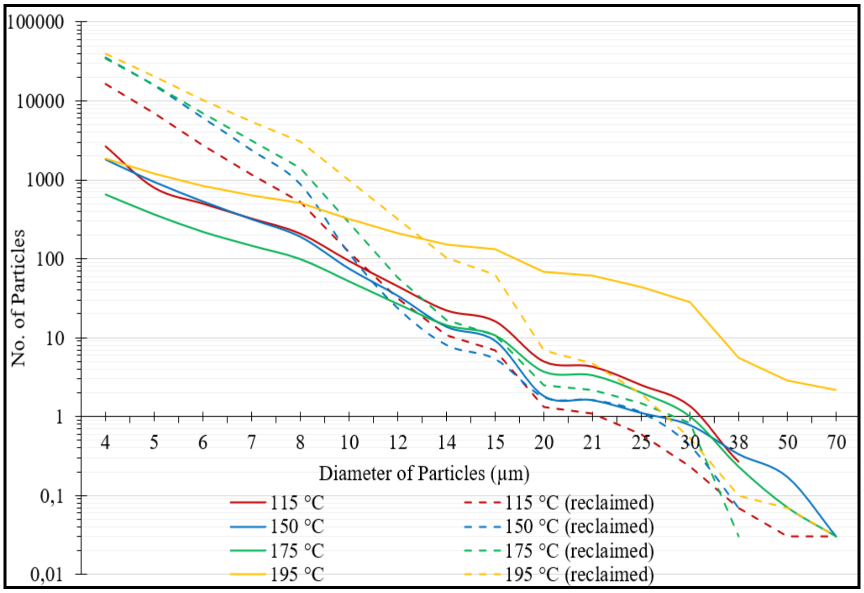


Figure VI-22: Particle count as a function of diameter for natural ester at different aging temperatures (°C).

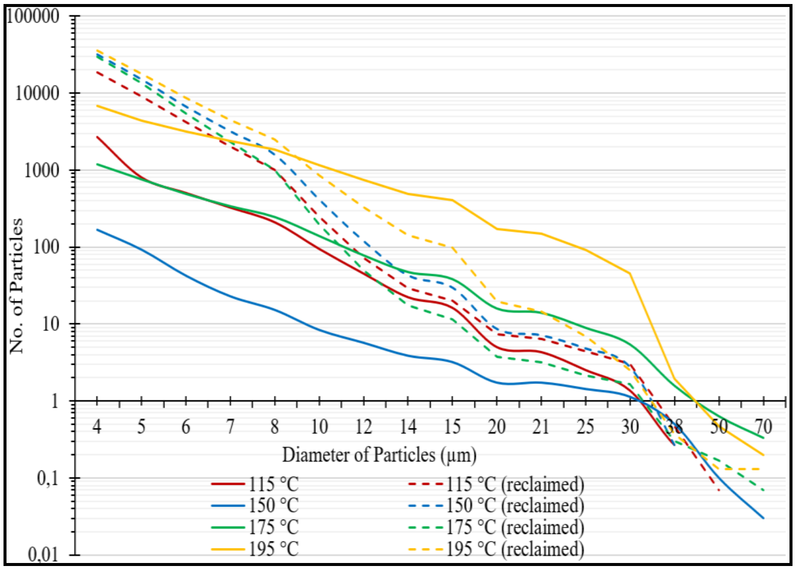


Figure VI-23: Particle count as a function of diameter for synthetic ester A at different aging temperatures (°C).

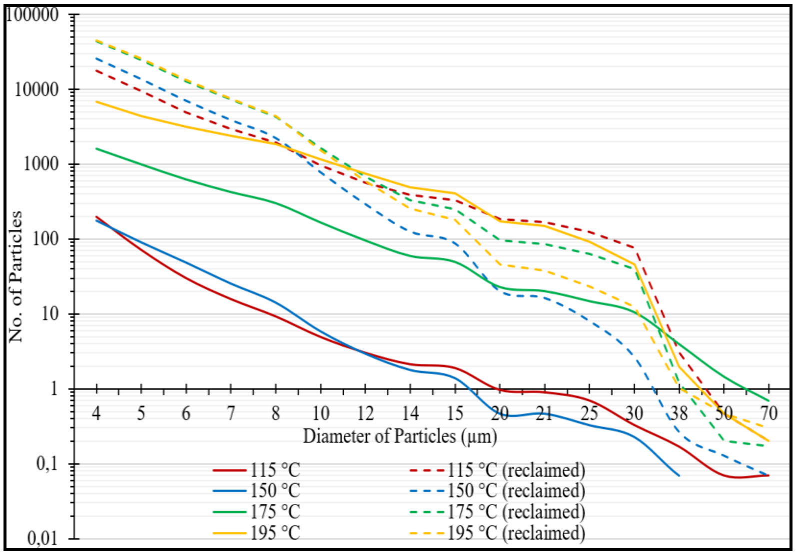


Figure VI-24: Particle count as a function of diameter for synthetic ester B at different aging temperatures (°C).

Additionally, the concentration and size of the smaller particles after filtration is almost the same. The reaction of an ester group or fatty acids in aged esters with hydrogen bonds on the rough surface of hydrous aluminum silicates (during filtration) may introduce further tiny particles. It is to be noted that single pass filtration is carried out for the present studies. Therefore, further analysis is required to comment on the increase in smaller particles with the treatment of ester fluids.

6.5 CONCLUSION

The effect of thermal aging on colloidal and dissolved particles is studied for mineral oil, natural ester, and two synthetic esters in an open environment in the presence of copper as a catalyst. The results of centrifugal treatment and fuller’s earth filtration are reported to enumerate colloidal and dissolved decay particles separately. For the aging factors considered in the present study, ester dielectric fluids have not witnessed colloidal particles. The obtained results depict the ability of esters to dissolve more sludge. On the other hand, despite being more prone to oxidation, natural ester generates lower amount of sludge compared to mineral oil. UV-vis spectral analyses indicate an excellent thermal stability of synthetic ester compared to both mineral and natural esters. However, soluble decay contents are involved with the deterioration of ester fluids. An increase in tiny particles is observed in ester dielectric fluids (natural and synthetic) based on filtration results. Even though larger diameter decay contents are separated with filtration, the suitability of fuller’s earth for filtration of esters is to be further investigated by focusing on the number of filtration cycles and pretreatment temperature.

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Chapter VII

CONCLUSIONS AND FUTURE SCOPE

Overview

This chapter presents the review of the prospective research findings accompanied by the discussion on key contributions of the present research. The future scope for the research on investigating the application in diagnosis of gassing for transformer insulation technology is also highlighted.

7.1 SUMMARY AND MAJOR FINDINGS

The global objective of the current PhD thesis was to demonstrate the influence of the aging byproducts on the physicochemical properties and the gassing tendency of the insulating fluids used in power transformers. In details:

a) Influence of low energy discharge faults (partial discharges);
b) Influence of arcing faults (high energy);
c) Influence of thermal faults (hot spot);
d) Influence of colloidal and soluble aging byproducts.

It was found that the fluid that is subjected to different stresses: thermal, low electrical discharge and high electrical discharge, the gassing is affected as the acidity content is increasing.

a) On a more specific base for low energy (partial discharge) faults, it was found that:

From the fresh class of mineral oil to a bad class of oil, there is an O_2 increases of 134 times. There is also an increase in N_2 of almost seven times. The changes in other gases go from 0.8 to less than two times, it is not significant as compared to O_2 and N_2. For synthetic ester, there is an increase of some gases such as CO_2, CH_4, C_2H_4, C_2H_6, C_2H_2. For natural ester, all gases decreased. All these changes in the quantity of gas should affect the results using the traditional diagnostic methods such as Duval triangle and Duval pentagon. It is to mention that the representation of natural ester is less affected by the displacement in the Duval tools compared to the mineral oil and synthetic ester.

b) On a more specific base for high energy faults, it was found that:

From the fresh class of mineral oil to bad class of oil, for synthetic ester, the volume of all gases increased except O_2 and N_2.

Similarly, for mineral oil, all the gases were increasing other than O_2 and N_2. It is to be mentioned that reference for per unit is based on the gas values for fresh oil. For natural ester, all gases increase except O_2, N_2, C_2H_6. These results are affecting the traditional diagnostic methods such as Duval triangle and Duval pentagon. It is to mention that the representation of natural ester is the less affected by the displacement in the Duval tools.

c) On a more specific base for thermal faults, it was found that:

From the fresh class of oil to bad class of oil, all gases increased except the unchanged of C_2H_2 and the increase of O_2. The synthetic ester is less affected by the thermal faults, but there are definitely some changes. H_2 and C_2H_2 did not changed. The volume of O_2 and N_2 decreased while that of the other gases increased. For NE, C_2H_2 did not changed, O_2 and N_2 decreased while the volume all the other gases increased. These results are affecting the traditional diagnostic methods such as Duval triangle and Duval pentagon. It is to mention that the representation of synthetic ester is less affected by the displacement in the Duval’s tools.

d) The influence of colloidal and dissolved particles:

For the aging factors considered in the present study, ester dielectric fluids have not witnessed colloidal particles. The obtained results depict the ability of esters to dissolve more sludge. Natural ester generates a lower amount of sludge compared to mineral oil. Soluble decay contents are involved with the deterioration of ester fluids.

The suitability of fuller's earth for reclamations of esters needs further investigations by focusing on the increase of the number of reclamation cycles and pretreatment temperature.

It was also found that the degradation of ester fluids is mainly governed by the generation of soluble particles, while the degradation of mineral oils is governed by the colloidal and soluble aging byproducts.

7.2 CONTRIBUTION TO LITERATURE

Four journal papers were published from this study:

Publication 1: **L. Loiselle**, U. Mohan Rao, I. Fofana, "Influence of Aging on Oil Degradation and Gassing Tendency for Mineral Oil and Synthetic Ester under Low Energy Discharge Electrical Faults," MDPI Energies, 13(3), pp.595, 2020.

Publication 2: **L. Loiselle**, U. Mohan Rao, I. Fofana, "Influence of Aging on Oil Degradation and Gassing Tendency under High Energy Electrical Discharge Faults for Mineral Oil and Synthetic Ester," IET High Voltage, 5(6) pp. 731 – 738, 2020.

Publication 3: **L. Loiselle**, U. Mohan Rao, I. Fofana, "Gassing Tendency of Fresh and Aged Mineral Oil and Ester Fluids under Electrical and Thermal Fault Conditions," MDPI Energies, 13(13), pp.3472, 2020.

Publication 4: **L. Loiselle**, U. Mohan Rao, I. Fofana, "Monitoring Colloidal and Dissolved Decay Particles in Ester Dielectric Fluids," IEEE Transactions on Dielectrics and Electrical Insulation, 27(5), pp. 1516-1524, 2020.

Two conference papers were published from this study:

Publication 1: **L. Loiselle**, G. Tapsoba, I. Fofana, "Suspended Particles in Oils under Electrical Discharge. Published in IEEE 19th International Conference on dielectric liquids (ICDL). Manchester, UK, June 25-29th 2017.

Publication 2: U. Mohan Rao, I. Fofana, **L. Loiselle**, "Preliminary Studies on Soluble and Colloidal Decomposition Products in Ester Filled Transformers" Published in IEEE 20th International Conference on dielectric liquids (ICDL). Roma, Italy, June 23-27th 2019, pp. 1-4.

7.3 LIMITATIONS

Once the scope of the project is defined, some limitations are required to fulfill the scope of the project. These limitations are:

- Artificially aged fluid was provided, it was a mix of extremely aged fluid with new fluids containing antioxidant;
- The average values of acidity for the different fluids were in the range from 0.082 to 0.098 for Proposition A and from 0.24 to 0.27 for bad fluid;
- The high energy stress was a series of 100 repetitions of breakdown voltage with 2 minutes intervals;
- The low energy stress apparatus (partial discharges) was settled to 9kV for a period of time of 5 hours;

- To simulate the thermal stress (hot spot), the apparatus was settled to 190 watts in order to limit the temperature to 250 °C for a period of 30 minutes. Twelve heating cycles have been done in a row;
- The particle counter measurement technique is not commonly used in the industry and in the research field. So, there are very little data for comparison in the literature.
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7.4 AREAS FOR FUTURE RESEARCH AND RECOMMANDATIONS

The proof of concept has been done with this PhD. In order to develop the tools required for maintenance, it is necessary to push these various points:

- The aging of fluid that was under investigation was limited in term of acidity values. To get much more information on the variations of gassing, it will be interesting to reach a higher level of acidity especially for natural and synthetic ester;
- The quantity of electrical high energy discharge can be extended to different repetition values;
- The low energy discharges can be adjusted to various time and various voltage. The geometry of the electrode can be changed as well;
- The temperature on the thermal stress (hot spot apparatus) can be changed to reach different values;
- A lot of data is required in order to be able to process into machine learning technique's algorithms. Furthers experimentations are required to tune the different tools that needs to be developed.