Experimental Assessment of Oil Regeneration Technique for Transformer Life Extension

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Ramamoorthi P Venkatasubramanian

School of Electrical and Electronics Engineering

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List of Abbreviations

2FAL	2-Furfuraldehyde
ACSD	AC voltage withstand test Short Duration
DP	Degree of Polymerisation
DT	Distribution Transformer
FE	Fuller's Earth
HAC	Hot Air Circulation
HMA	High Molecular weight Acid
HOC	Hot Oil Circulation
KF	Karl Fischer
LFH	Low Frequency Heating
LI	Lightning Impulse
LMA	Low Molecular weight Acid
NN	Neutralisation Number
NS	Number of chain Scissions
ODMS	Online Drying with Molecular Sieves
PD	Partial Discharge
RH	Relative Humidity
TAN	Total Acidity Number
TI	Tensile Index
TS	Tensile Strength
VPD	Vapour Phase Drying

Abstract

With a large population of ageing transformers, utility asset managers are becoming increasingly interested in techniques which can help prolong the life of the transformer and optimize its efficiency in terms of economic operation and long-term performance. The performance of a transformer is affected by the condition of the insulation, which in turn affects the reliability of the network. The ageing of oil and paper results in the generation of ageing products such as moisture and acids, which further accelerate the ageing process through cyclic reactions. Thus, these ageing by-products need to be removed from the system at an appropriate stage in order to ensure the long-term performance of the transformer by slowing down the ageing process. This can be achieved through several measures, of which oil regeneration is becoming popular.

In order to study the long-term effect of oil regeneration, oil samples collected from an on-site regeneration exercise performed on a 132/33 kV transformer were utilised in a laboratory-accelerated thermal ageing experiment. Oil samples collected before and after the regeneration were aged alongside new oils for comparison. Key ageing indicators, namely Total Acidity Number (TAN), moisture, Low Molecular Weight Acid (LMA) content, and High Molecular Weight Acid (HMA) content for the oil, and moisture, Low Molecular Weight Acid (LMA) content, and Tensile Index (TI) for paper were measured regularly. It was found that performance of oil after regeneration is better than that of oil before regeneration, and is even comparable to that of new oils. Slower reduction of TI of paper aged in oil after regeneration than paper aged in oil before regeneration conforms to previous findings that oil condition plays a role in determining the ageing rate of paper, and supports the statement that oil regeneration can slow down paper degradation in transformers.

Oil regeneration experiment was performed on a 6.4/0.4 kV 77-year-old retired distribution transformer. Oil regeneration was conducted in two stages (stage 1 and stage 2), with the first stage aimed at ‘cleaning’ the oil and the second stage targeted at ‘cleaning’ the paper. Oil samples were collected at regular intervals throughout the process, and paper samples were collected from the transformer before oil regeneration, after stage 1, and after stage 2 of oil regeneration. It was found that oil regeneration restores oil parameters, including moisture and acidity, similar to those of new oils. Analysis of paper samples indicated a reduction in paper moisture at the end of stage 2 by nearly 40%, while LMA in paper exhibited a reduction at the end of stage 2 by around 30% on average. Similar reductions of paper moisture and acid content in the laboratory-conditioned samples provided strong evidence to the notion that oil regeneration is capable of improving the paper condition, and subsequently reduce the ageing rate of the paper insulation.

It was concluded that strong evidence has been presented to show the effects of oil regeneration techniques on improving the conditions of both oil and paper under the investigated conditions. Therefore, it could be an effective way of managing the ageing asset population.

Declaration

I declare that that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright Statement

Acknowledgement

I wish to thank my supervisor, Dr. Qiang Liu, for his guidance, and all his efforts and time invested into my academic and personal development. I also wish to express my sincere gratitude to my co-supervisor, Prof. Zhongdong Wang, for her guidance, support, and encouragement throughout the course of my study.

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I express my gratefulness towards my friends and colleagues, who provided strong moral support during difficult times. Finally, my deepest gratitude to my family, for always believing in me and looking out for me.

Chapter 1. Introduction

1.1 Background

Transformers play a key role in integrating the power grid and in ensuring continuous operation of the power network. With the world moving towards a more resilient power network, the reliability of each network component becomes of utmost importance in ensuring uninterrupted power supply to the consumers. There is an increased interest in studying the ageing behaviour of transformers, given their importance in the power system. These studies help gain valuable insights which could aid in prolonging the life of these assets and maintaining their reliability [1]. Ageing studies are gaining further prominence recently due to the large population of ageing assets in operation.

The investment boom of the 1960s and 70s resulted in rapid industrialisation, which, to a large extent, governed the development of today's power networks and associated components [2]. As a consequence, a majority of the transformers in operation in the UK power systems are crossing their design age. Market deregulation and an increased competition has urged utility operators to look into optimising the utilisation of their equipment in terms of operating efficiency and cost-effectiveness [3]. In response to this requirement, utility operators and service providers have adopted asset management techniques, targeted at enhancing the usage of the residual life time of the asset, with particular attention to ensuring reliability of service, and distribution of maintenance and re-investment costs [3]. Due to the high value and large population [4], transformers are one of the main assets in the focus of asset management entities.

A majority of transformers in service today are of the oil-immersed type, with cellulose as the solid insulation. The oil, apart from functioning as a coolant, also serves as an electrical insulation. The ageing of a transformer is mainly governed by the ageing of the paper and oil insulation system. As oil and paper age, they generate ageing by-products such as acids and moisture, the accumulation of which further accelerates the ageing process. Thus, it is imperative that these ageing by-products are identified and removed from the system at an appropriate stage in order to slow down the ageing process. A utility can exercise various intervention techniques to

improve the condition of the oil and paper by the removal of moisture and acidic by-products of ageing. Of these techniques, oil regeneration has recently become more attractive as a life extension measure in order to defer investment costs.

1.2 Problem Statement

Several factors are to be considered when choosing an intervention technique including the duration of the maintenance, on-line and off-line preferences, investment and operating costs, and the efficacy of the chosen technology against the intended purpose. Thus, it is important to understand the pros, cons, and the long-term effects of these technologies on the insulation in order to enable utilities and asset management entities to make an informed decision. However, a large extent of these studies have been limited due to the difficulties in obtaining insulation samples, particularly cellulose paper, from the transformer when it is still in-service. A few studies which have been reported are restricted to improvement in oil acidity and moisture [5, 6]. There have been minimal investigations into the effect of intervention techniques on the moisture and acidity of the solid insulation, and the long-term performance of the insulation system post-reconditioning.

1.3 Research Objectives

In order to justify the choice of a suitable insulation reconditioning technique, a broad review of the common intervention technologies and related case studies is presented as a preface to the research. Following the choice of the intervention technique (adsorbent-based oil regeneration), the investigation is proceeded to satisfy the following two objectives:

i) <u>Investigation on the long-term ageing performance of oil after regeneration</u>

This part of work is an extension of the previous study of [7], where oil regeneration was performed on a 44-year-old in-service 132/33 kV transformer. Using the samples obtained from this study, it is possible to investigate the long-term ageing performance of the oil after regeneration through laboratory-based accelerated thermal ageing experiments. By controlling the composition of the ageing system, it is possible to mimic the ageing of the oil-paper insulation system in a real-time transformer. The long term performance of the service-aged oil before and after

regeneration can be established alongside those of new mineral oils, in order to enable the comparison.

ii) Investigation on the effects of oil regeneration on paper conditions

There is a lack of evidence to support the estimated life extension achievable through oil regeneration. It is widely accepted that a mere improvement in the oil parameters alone is insufficient in effectively reducing the ageing rate of the transformer, as the paper condition plays a more crucial role in deciding the remaining life of the transformer [8]. This is highlighted by the existing ageing and life estimation models, which focus on the paper parameters such as moisture and Degree of Polymerisation (DP) to estimate the life of the asset [9, 10]. Thus, it is necessary to investigate the changes to paper ageing parameters, particularly through moisture and Low Molecular weight Acid (LMA) measurements (the latter of which has been recently suggested to greatly influence ageing of the paper) in order to quantify the improvement in conditions through oil regeneration. This could be made possible through post-mortem analysis of retired transformers, which allows for non-invasive and invasive methods of investigating the condition of the solid insulation. By subjecting the transformer to intervention procedures, the changes to the paper parameters can be studied directly through sampling before and after oil regeneration.

1.4 Outline of the Thesis

This thesis is organised into 5 chapters. An outline of the focus of each chapter is provided below.

Chapter 1: Introduction

This chapter provides an overview of the background and the motivation behind this study. The objectives of the research are established, and an outline of the thesis is presented.

Chapter 2: Literature Review

In this chapter, a review of relevant published work is presented on two topics – ageing of transformer insulation, and transformer intervention techniques. Following this, case study analysis of transformer reconditioning is presented, sourced from various industrial reports and literature-reported studies.

Chapter 3: Ageing Assessment of Regenerated Oil

Utilising the samples collected from a previous on-site oil regeneration study [7], an ageing experiment is designed to compare the long-term performance of the oil before and after regeneration. An oil-paper-copper system is utilised to mimic the insulation system used in a real-time transformer. Further, a variety of new mineral oil samples are also aged alongside these oils in order to enable comparison of their long-term performance with that of the oil after regeneration.

Chapter 4: Effect of Oil Regeneration on Paper Conditions

Oil regeneration procedure is performed on a 77-year-old retired transformer. Paper samples from the windings are collected before and after the transformer is subject to oil regeneration procedure. Additionally, the changes to oil moisture and temperature during the oil regeneration are monitored dynamically using sensors installed within the transformer tank. Analysis of key ageing indicators of the paper samples collected from the windings provides insight into the effect of the oil regeneration process on the paper. Furthermore, paper samples pre-conditioned in the laboratory help gain a solid understanding of the effect of oil regeneration by controlling the initial paper parameters such as acidity and moisture.

Chapter 5: Conclusions and Future Work

This chapter presents a summary of the work carried out in this MPhil research, from which the conclusions of the study are drawn. Suggestions for future work are been proposed, in the interest of employing these techniques in a real-time situation.

Chapter 2. Literature Review

As a preface to the studies undertaken in this research, a literature review is presented in this chapter. The literature review is grouped according to the content as ageing of transformer insulation, transformer intervention techniques, and case studies of transformer insulation reconditioning.

2.1 Background

Transformers broadly consist of two different types of insulation – oil and cellulose. The latter is present in the form of solid insulation, namely, the paper and pressboard. Apart from this, the transformer construction requires various metals, like copper, iron, etc. which form the principle components of the core and the windings.

2.1.1 Liquid Insulation (Oil)

Presence of oil in the transformer serves several purposes, the most crucial of which is to provide insulation strength to the transformer. Apart from this, oil also functions as a coolant, and an information career which can be used for condition or health diagnostic purposes.

This study focuses on mineral oils, which are used extensively in transformers for over a century [11]. Mineral oils are composed of refined hydrocarbon based oils, with additives to improve the performance. An example of such an additive is the inhibitor, which is added to curtail the oxidation process, thereby increasing the life of the oil.

Crude oil is a mix of numerous hydrocarbon compounds, apart from containing smaller quantities of compounds like sulphur, oxygen, nitrogen, iron, etc. [12]. Mineral oil is a by-product of the distillation of the crude oil, and can be classified into three types as Paraffinic, Naphthenic and Aromatic. Of these, naphthenic oils are more commonly used due to varying factors such as abundance, lower pour point and higher solubility of sludge [11].

2.1.2 Solid Insulation (Paper)

As previously mentioned, cellulose in the transformer is present mainly in the form of paper and pressboard. These components play a prominent role in the provision of electrical insulation and mechanical stability.

Insulation grade paper is made from wood by the Kraft process, or sulphate process [13]. About 90% of this paper is cellulose, 6-7% is lignin and the rest is pentosans[14]. In transformers, cellulose exists mainly in the form of Kraft paper and pressboard. Kraft paper, which is the major insulator wrapped over the conductors, consists of cellulose, hemicellulose and some residual thiolignin, remnants of the paper pulping process [15].

Cellulose consists of β-D-glucopyranosil units which occur in the form of linear polymeric chains (Figure 2-1 [16]). The number of such chains is represented by the Degree of Polymerisation (DP).

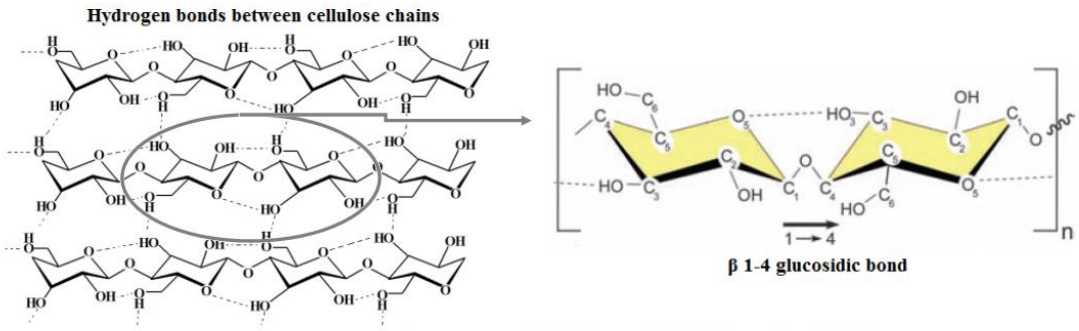


Figure 2-1 Cellulose polymer [17]

Cellulose can be represented as $[C_5H_{10}O_5]_n$, ignoring the extra atoms in the end group. Here, n represents the DP. Higher value of DP represents a higher mechanical strength of the paper. The repeating unit consists of two glucose units, and is called cellobiose [16], which are held in place through hydrogen bonding.

The sulphate process results a slightly alkaline residue in paper due to the sulphate content. Quality and strength of the paper produced vary widely between manufacturers, who employ different technologies and processes for production [13]. The various solid insulation components of the 220 kV side of a 400/220 kV transformer are shown in Figure 2-2 [18]. Cellulose performs the dual function of

providing insulation to the windings and simultaneously providing mechanical support to the winding while protecting it from physical damage [19, 20].

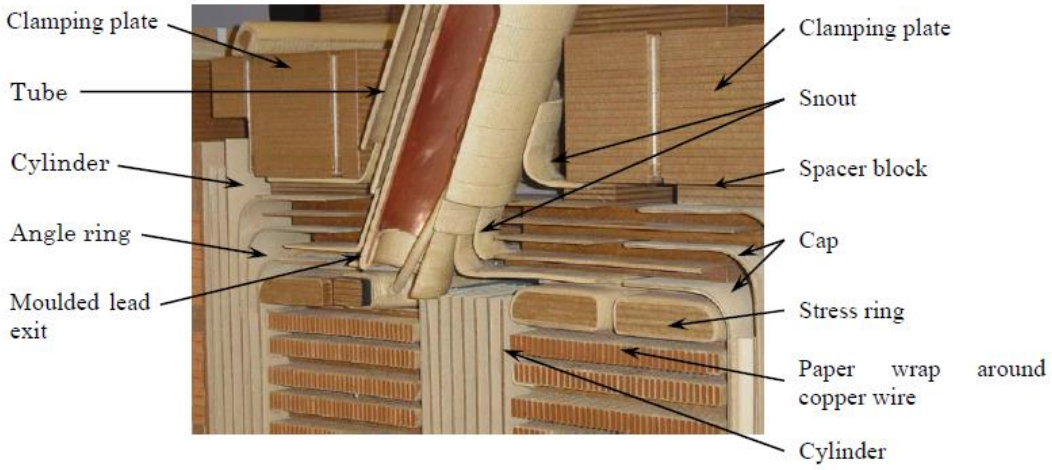


Figure 2-2 Insulation components of the 220 kV side of a 400 kV/220 kV transformer [18]

2.2 Ageing of Transformer Insulation

It is desirable that the oil in the transformer lasts as long as the transformer does. As oil and paper age, they generate degradation products. Further, the existence of copper and the other metallic elements in the transformer could influence the rate of insulation ageing.

According to IEEE loading guide for Mineral Oil Immersed transformers [21], it was suggested that the definition of end-of-life of a transformer be made based on measureable mechanical, dielectric and chemical characteristics. These characteristics are further discussed in this section.

2.2.1 Transformer oil ageing

2.2.1.1 Oil ageing process

Degradation of the hydrocarbons in the oil can be caused by several factors such as exposure to air, high operating temperatures, atmospheric moisture ingress, and presence of metallic compounds such as iron, copper and lead. This oxidative degradation of the oil is the major cause of reduction in the insulating properties, and is illustrated in Figure 2-3 [12].

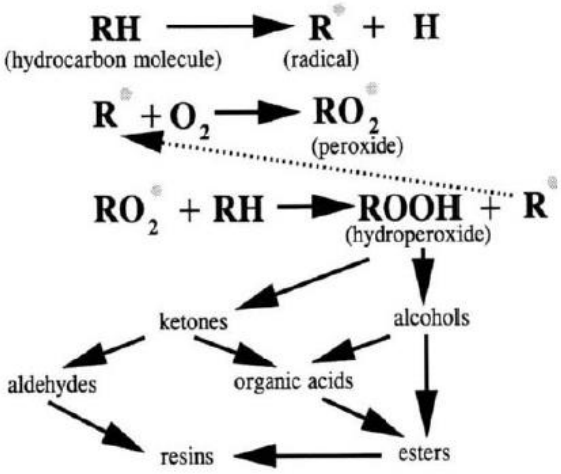


Figure 2-3 Mechanism of hydrocarbon oxidation in mineral oil [12]

The degradation process is triggered by the appearance of a hydrocarbon radical (R•), which is called the initiation stage. The next stage is propagation, where the hydrocarbon radical reacts with any oxygen present to form peroxy radical (RO_2•). The peroxy radical can then further react with existing hydrocarbon molecules to form hydroperoxide (ROOH). A free radical is also produced as a by-product of this reaction. The final stage of oxidation is termination, where the hydroperoxides degenerate to form ketones and alcohols, which in turn lead to organic acid formation, or an aldehyde leading to resin formation. Organic acids can also give rise to esters, which can in turn lead to resin formation too. Oil oxidation can cause deposit (sludge) formation, oil thickening, lacquering and an increase in oil acidity. [12]

Synthetic phenolic radical scavengers can be used to slow down the oxidation rate. This process is called inhibition, and oils with added inhibitors are consequently called 'inhibited' oils. If these radical scavengers are not used, the oil is termed to be 'uninhibited'. However, compounds such as thiophenes and organic sulphides, which are present in the oil after the refining process, provide natural oxidation inhibition properties to uninhibited oils. While in an uninhibited oil, the oxidation begins from day one, oxidation of inhibited oils is much slower until the inhibitors are consumed. Once this stage is reached, oxidation occurs at a much more rapid rate [1, 22].

2.2.1.2 Factors affecting oil ageing

Ageing of oil is primarily influenced by oxygen, water/moisture, temperature, presence of metal, and inhibitor content.

1) Effect of oxygen

The amount of oxygen that can influence the oxidation process of transformer oil directly depends on the design of the transformer. In the UK, a vast majority of the transformer are free-breathing by design. A hermetically sealed system can be applicable only to smaller sized transformers, like distribution transformers. The larger transformers, with the exception of those designed with nitrogen blankets, will be exposed to air to a considerable extent. Thus, some oxygen will be constantly be dissolved in the oil [22].

The acidity value of oil as a function of age for a range of free-breathing and sealed transformers is presented in Figure 2-4 [22]. It is noted that the absolute value of acidity for free-breathing transformers is significantly higher than that for sealed transformers for the same given age. It is clear from Figure 2-4 [22] that the acidity of oil for free-breathing transformers increases at a faster rate when compared to sealed transformers

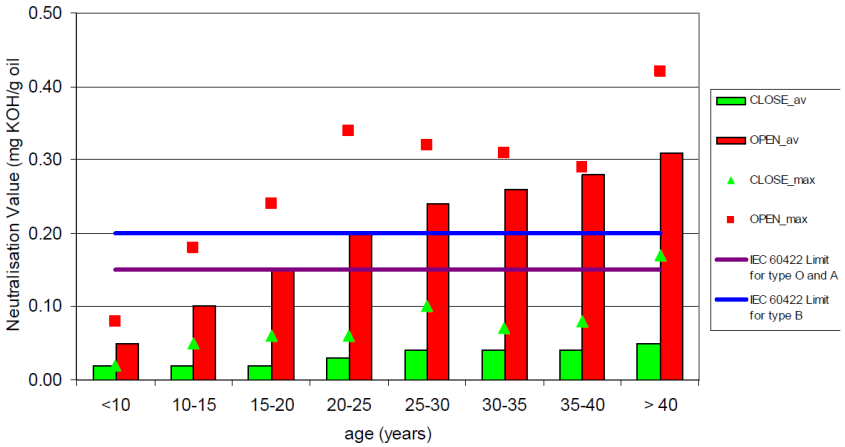


Figure 2-4 Acidity (neutralisation value) as a function of age for free-breathing (OPEN) and sealed (CLOSED) transformers [22]

2) Effect of temperature

Apart from oxygen, the oxidative degeneration of oil is highly dependent on the temperature, as every reaction is thermally dependent on the Arrhenius law [22]. Higher temperatures result in acceleration of the oxidation process [1], as well as providing more activation energy for the ageing process [15]. Like most chemical reactions, the rate of oxidation (measured as rate of oxygen absorption) approximately doubles when the temperature increases by 7 ℃ - 10 ℃ [22].

3) Effect of water/moisture

It is commonly reported that the ageing rate of oil increases when the initial moisture content in paper is higher [14, 15, 23, 24], accompanied by a subsequent reduction in the dielectric properties of the oil [25, 26]. This is demonstrated in Figure 2-5 [15], where the increase in acidity of oil is shown for different initial water contents in paper.

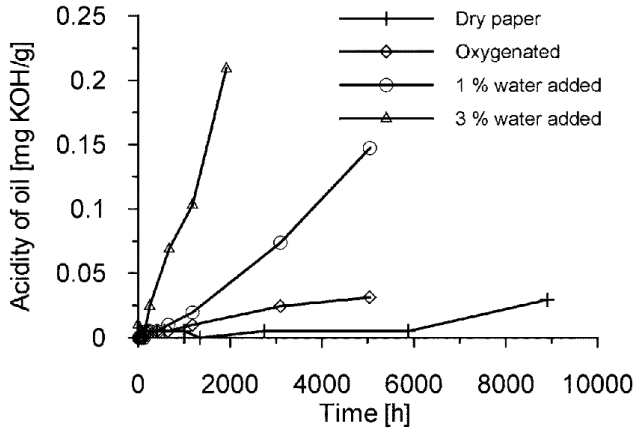


Figure 2-5 Acidity in oil for different levels of initial moisture in paper at 130 ℃ [15]

From Figure 2-5 [15], it can be inferred that the acidity of oil increases at a faster rate as the moisture content in the system increases. Oxidation of oil not only generates more polar ageing products such as acids, but also promotes water emulsification thereby increasing water solubility. This can in turn affect the dielectric properties of the oil, and also have a negative effect on paper ageing.

4) Effect of metals

Presence of metals in the system can have a catalytic effect on the ageing process. Oil oxidation products, such as water and peroxide, influence the corrosion of the metallic components of the transformer like copper and iron. The corrosion of these metals can then lead to further oxidisation of the oil, in turn leading to increased corrosion. This cycle of degradation can be controlled by the addition of metal passivators, which have also been shown to enhance the oxidative stability of uninhibited oils [22].

5) Effects of inhibitors

Inhibition of mineral oil involves the addition of certain anti-oxidants, which combat the oxidative by-products in the system and slow down the ageing process. A

common inhibitor that has been long used in transformers is DBPC (Diteriary-Butyl-Para-Cresol) [27].

It is fact that inhibitors only slow down, but not entirely stop, the oxidation of the mineral oil. Studies were conducted on the possible life extension achieved by the utilisation of inhibitor additives [28-30]. A statistical plot of the increase of acidity with age for an inhibited and uninhibited transformer is shown in Figure 2-6 [1] and Figure 2-7 [1] respectively. These studies were conducted by Nynas [1] by examining a total of 164 assets, a mix of inhibited and uninhibited oil-based transformers.

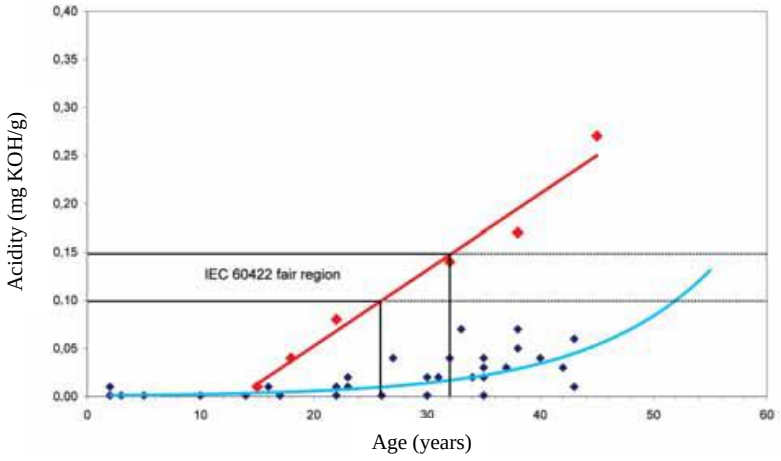


Figure 2-6 Acidity trend for inhibited oils [1]

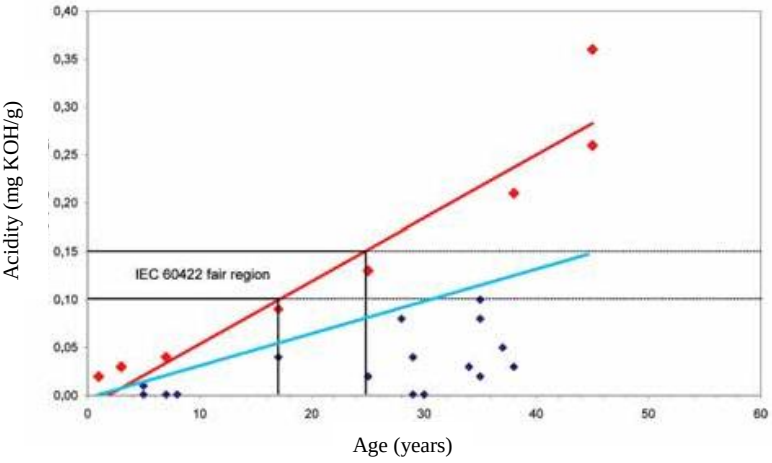


Figure 2-7 Acidity trend for uninhibited oils [1]

The red line in Figure 2-6 [1] and Figure 2-7 [1] are the linear regression which represent the worse-case scenario only, while the blue lines represent the best fit of all the data. Furthermore, it is noted that the worst-case scenario for the inhibited oil is shown only from the point of accelerated ageing. It can be observed that the ageing of uninhibited oils occurs at a steady rate, while in case inhibited oils, the ageing rate

is slow until the inhibitor additives are completely consumed. Beyond this point, oxidation starts and ageing occurs at a much faster rate.

2.2.2 Transformer paper ageing

2.2.2.1 Cellulose ageing process

The ageing process of cellulose can be summarised as three mechanisms – hydrolysis, oxidation and pyrolysis.

1) Hydrolysis

It has been widely suggested that acid-catalysed hydrolysis is the major mechanism of paper ageing in a transformer [31-36]. Figure 2-8 [37] demonstrates the mechanism of hydrolysis in cellulose.

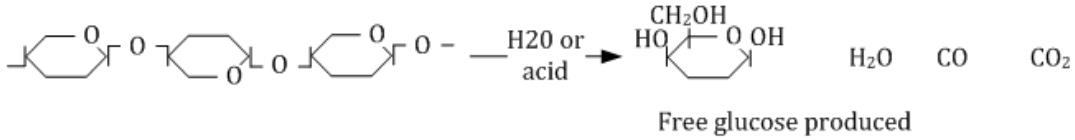


Figure 2-8 Mechanism of hydrolysis in cellulose [37]

Hydrolysis involves the cleavage of Hydrogen, described as a catalytic reaction with the aid of the acid by-products of both oil and cellulose degradation [31, 32]. Further, under the presence of acid, the cellulose linkages are hydrolysed rapidly and produce more by-products including water and carboxylic acid, which effectively makes hydrolysis a self-catalysed process. It was found that water is more imperative to the ageing process, when compared to oxygen [15], thus making hydrolysis the dominating ageing mechanism of paper.

2) Oxidation

Figure 2-9 [38, 39] shows the mechanism of oxidation in cellulose. Oxidation will commence once the hydroxyl groups in cellulose structure are attacked by oxygen, which weakens the glycosidic linkage. Moisture is the primary ageing product through oxidation, while secondary ageing products include carbonyl and carboxyl groups. These groups will promote hydrolysis in paper and oil.

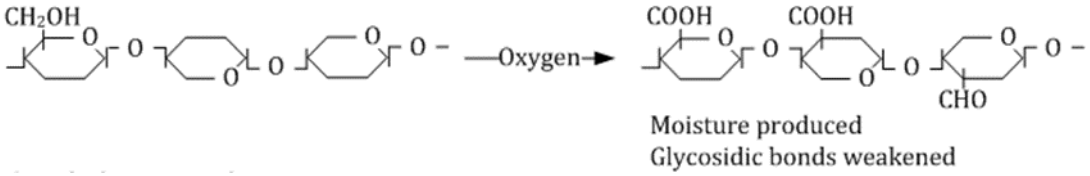


Figure 2-9 Mechanism of oxidation in cellulose [38, 39]

There are many intermediates in the oxidative process. Three of them, 2-furfuraldehyde, 5-hydroxymethyl-2-furaldehyde, and carbon monoxide [40], are also produced non-oxidatively [41]. Others seem to be produced exclusively by oxidation, and their identities therefore have diagnostic significance. They include 5-methyl-2-furaldehyde, 2-acetylfuran, and 2-hydroxymethylfuran (furfuryl alcohol). Oxidative depolymerisation is catalysed by hydroxyl-radicals, which are produced by decomposition of hydrogen peroxide. Oxidation of the solid insulation can result in sludge formation, apart from the production of acids.

3) Pyrolysis

The mechanism for pyrolysis in cellulose is illustrated in Figure 2-10 [38, 39]. Pyrolysis is a form of 'slow combustion', defined as the thermal degradation of the material at elevated temperatures in the absence of oxygen.

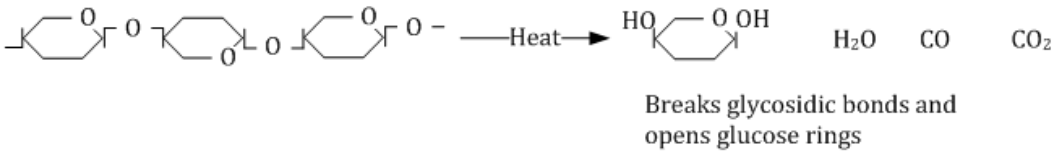


Figure 2-10 Mechanism of pyrolysis in cellulose [38, 39]

Pyrolysis is not a factor which greatly affects the ageing of a transformer as it normally occurs at temperatures of over 140 ℃. Thus, unless a fault develops, the effect if pyrolysis on paper ageing can be deemed to be insignificant.

2.2.2.2 Factors affecting paper ageing

Ageing of paper is influenced primarily by four factors – water/moisture, acids, and temperature.

1) Effect of Water/Moisture

There are two sources for moisture in a transformer – as a by-product of the ageing process, and by ingress from the environment. A substantial number of transformers used today are free-breathing by design. This would mean a constant moisture ingress

into the tank and a subsequent increase in the moisture content of the oil. This, in turn, leads to increased moisture content in the paper which promotes ageing.

Water in oil is conventionally measured in parts per million (ppm). Insulating liquids have a lower affinity for water, but the water solubility increases with temperature. When the quantity of water in oil exceeds the saturation quantity, the excess water will be precipitated and exist as free water [42]. Moisture in paper can be much more than that in oil, since paper is naturally hydrophilic while oil is hydrophobic. Moisture in paper is usually expressed in % of weight of moisture to the weight of the dry paper/pressboard. The majority moisture in a transformer system is contributed by the paper.

The effect of initial moisture content in oil and paper on the ageing process is widely studied [26, 42-56]. It was demonstrated by Emsley et al. [57] that a higher initial moisture content in the paper results in the quicker reduction of DP, as seen in Figure 2-11 [57]. Further evidence for the impact of moisture in the rate of degradation of paper strength was provided by Hohlien and Kachler [26], who demonstrated the percentage reduction in DP for different initial moisture contents, shown in Figure 2-12 [26]. Figure 2-11 [57] and Figure 2-12 [26] demonstrate that the presence of more moisture in the system accelerates the paper degradation process.

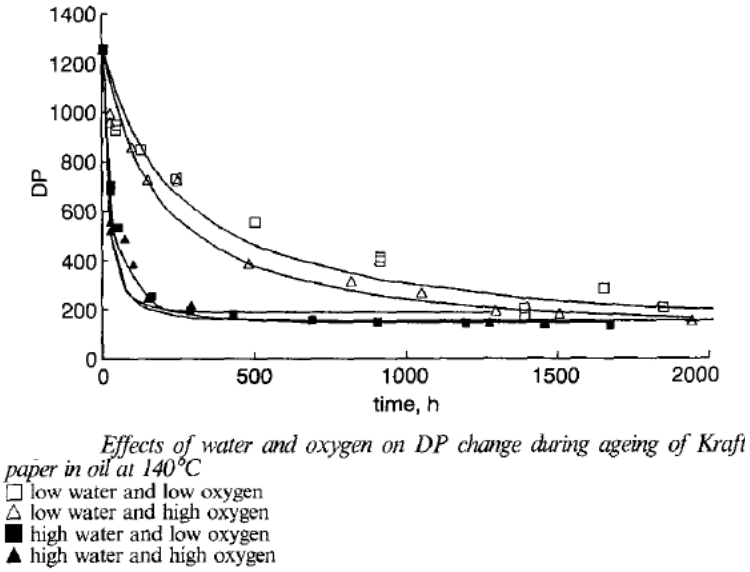


Figure 2-11 Effects of water and oxygen on DP change during ageing of Kraft paper in oil at 140 ℃ [57]

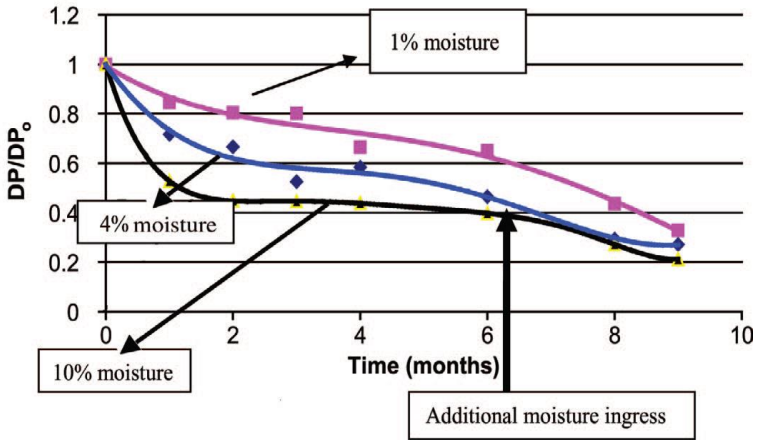


Figure 2-12 Effect of varying initial moisture content on DP during ageing at 95 ℃ (DP_0 represents the DP value of pressboard prior to ageing) [26]

2) Effect of Acids

It is widely premised that acids have a negative effect on the ageing rate of paper. Acids can be classified as Low Molecular weight Acids (LMA) and High Molecular weight Acids (HMA) [31, 32, 34]. In general, acids with molecular weight ranging from 46 to 116 g/mol (e.g. formic, acetic and laevulinic acids) are classified as LMA, while those with molecular weight ranging from 240 to 285 g/mol (e.g. stearic and naphthenic acids) are classified as HMA. Most of LMA tends to stay in the paper while most of HMA tends to stay in the oil. It was demonstrated through accelerated thermal ageing experiments by Lundgaard et al. that LMA has a much higher impact on the paper ageing than HMA [31, 32, 34]. These findings are shown in Figure 2-13 [31]. It was concluded that the naphthenic and stearic acid, which are HMA and are hydrophobic by nature, do not affect the ageing compared to the reference experiment without any acid content. LMA, which are hydrophilic acids, was shown to have a significant impact on the reduction of the paper DP value. It was further suggested that the impact of the acid increases with the reduction in acid molecular size. This effect was attributed to the ready absorbability of the LMA into the cellulose fibres due to higher polarity. These results were further confirmed by Azis et al. in terms of paper tensile index through similar laboratory accelerated thermal ageing experiments, shown in Figure 2-14 [58].

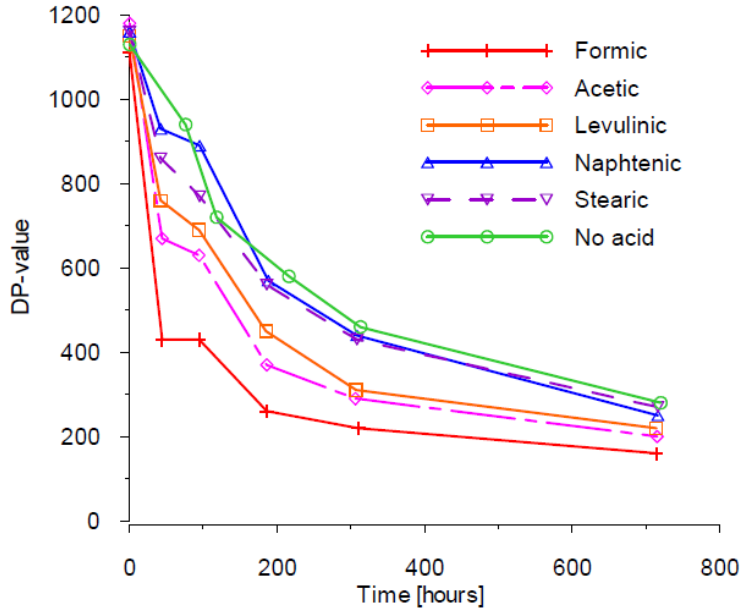


Figure 2-13 Effect of different acids in oil on paper ageing under wet conditions at 130 ℃ [31]

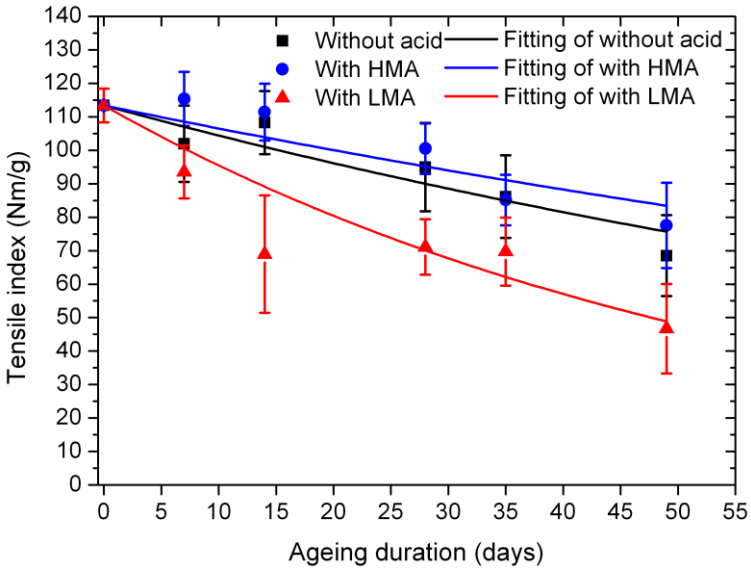


Figure 2-14 Effect of different acids in oil on paper ageing under dry conditions at 110 ℃ [58]

3) Effect of Temperature

Similar to oil oxidation, ageing of paper is heavily dependent on the temperature. Lundgaard et al. [15] demonstrated the effect of temperature on the ageing of paper in an oil-paper system, as shown in Figure 2-15 [15]. It is noted that in an in-service transformer, the effect of temperature might be significantly less dominant, given that extreme high temperatures occur only in the case of faults or poor design.

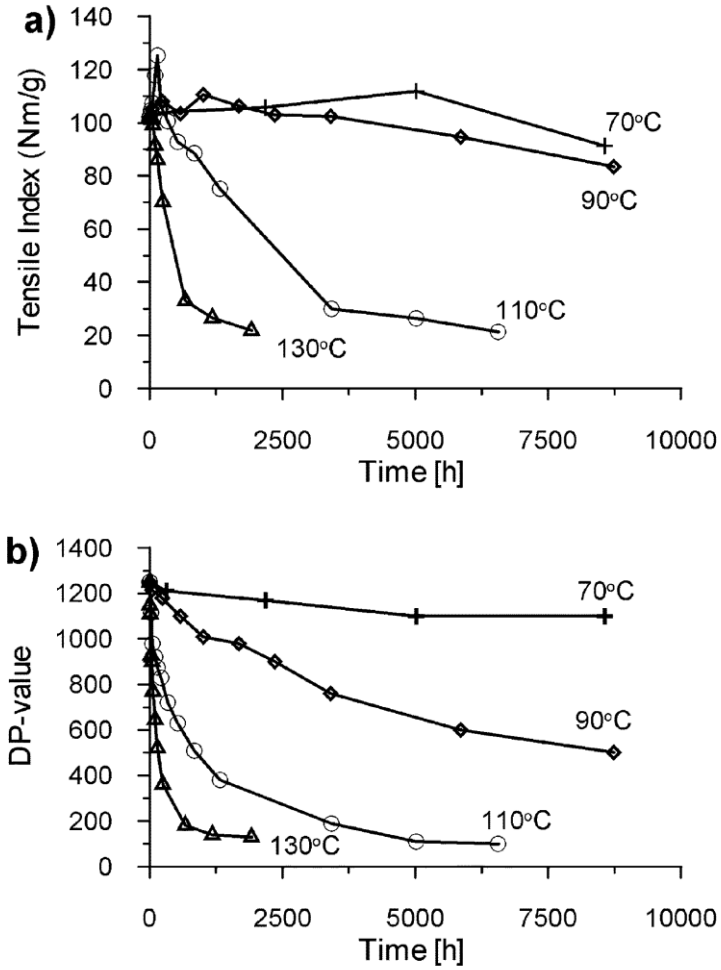


Figure 2-15 (a) Tensile Strength and (b) DP profile for kraft paper at different temperatures of ageing; 3% moisture added [15]

2.2.3 Ageing of oil-paper insulation system in transformers

While ageing is a term that is generic to both the oil and solid insulation of a transformer, the ageing of solid insulation is comparatively more influential on the age of the transformer. This stems from the fact that while oil can be purified/reclaimed from time to time, or even replaced when necessary, paper and other solid insulation components form a permanent, irreplaceable part of the transformer. Thus, their degeneration would signify a much greater and irreversible impact on the life of the transformer. The ageing of oil and paper in a transformer is a complex cyclic phenomenon, summarised in Figure 2-16 [59].

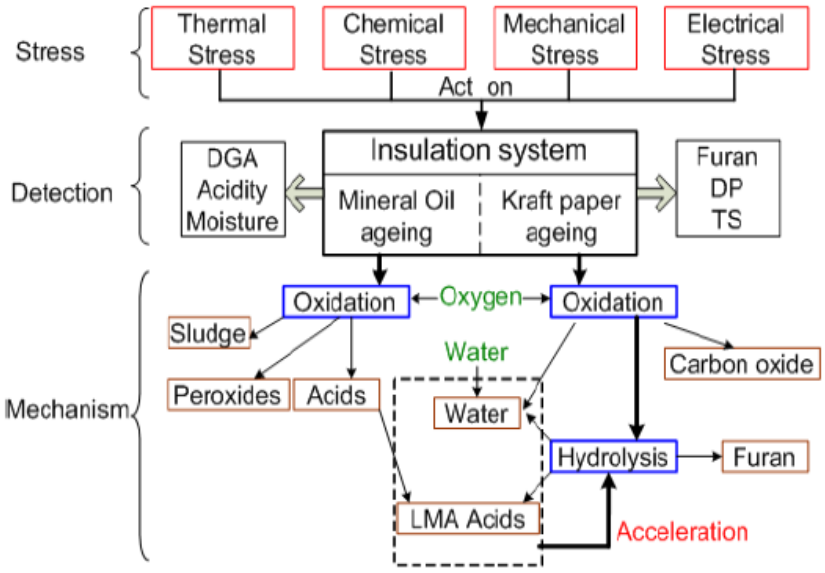


Figure 2-16 Factors influencing the ageing of the oil-paper system [59]

Multiple factors including thermal, chemical, mechanical and electrical stresses influence the ageing of paper and oil. It was previously established that the primary ageing route for the oil insulation is oxidation, and that for paper are through hydrolysis and oxidation. The by-products of oxidation include water and acids of the carbonyl and carboxyl type [31, 32, 60], the latter of which is classified as LMA and HMA. Water, which is also a major by-product of the oxidation process, aids in the dissociation of the LMA by increasing the H^+ ion content in the system, and thereby initiating hydrolysis of the paper. Hydrolysis is a self-catalytic reaction and leads to further acid, water, and furan production. On the other hand, oxidation of paper and the oxidation of oil is regarded as self-suppressing as the production of acids progressively supress the production of hydroxyl radicals, which function as a catalyst for oxidation.

2.2.4 Transformer ageing indicators

Ageing affects both the oil and the paper insulation in the transformer. The effects of ageing can exist as chemical by-products, or it can affect intrinsic electrical and physical parameters of the insulation. IEC 60422 and IEC 60554 standards provide benchmark for assisting in the evaluation of the transformer condition through the testing of oil and paper properties respectively. However, it is noted that several chemical ageing indicators which have also been utilised in this study, are recently proposed and have therefore not been incorporated into the standards. In this research,

the evaluation methods are restricted to certain chemical, physical and mechanical properties of the oil and paper.

The commonly used chemical ageing indicators include acidity, water/moisture, and furanic content. Common physical ageing indicators include colour of the oil and DP of the paper. Tensile strength is a mechanical property of the paper which is also used to determine its health.

2.2.4.1 Chemical ageing indicators

1) Acidity

Acidity is a common ageing indicator for both oil and paper. It was established that acids are a chief by-product of the aging of both oil and paper, classified as LMA and HMA. It was also established that the LMA tends to largely originate from paper ageing, while HMA primarily originates from oil ageing. Most of the LMA tends to stay in the paper, while most of the HMA tends to stay in the oil.

Acidity in oil can be measured according to IEC 62021 [61], where the term 'Neutralisation Number' (NN) or Total Acid Number (TAN) is employed as the measurement parameter through potentiometric titration. TAN or NN is defined as the amount of potassium hydroxide (KOH) in mg required to neutralise the acid content of 1 gram of the oil sample. A typical trend for oil acidity with the transformer age is shown in Figure 2-17 [62].

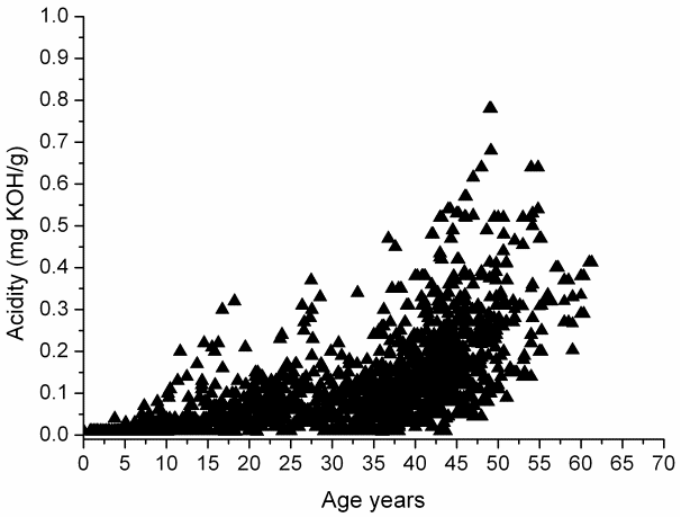


Figure 2-17 Typical acidity vs transformer age trend [62]

The acidity in oil can also be separated into LMA and HMA by employing a polar liquid extraction technique, which was suggested by Lundgaard et al. [32]. This

process involves utilising a polar solvent, such as water, to extract the polar LMA content and then titrating it to get the change in acidity of the water.

Lundgaard et al. also suggested the measurement of LMA in paper as an ageing indicator [15, 31, 32]. LMA in paper can also be measured using a similar polar extraction technique. Azis et al. [63] also presented a relationship between the TI and LMA in paper based upon data collected from in-service ageing and laboratory ageing experiments, shown in Figure 2-18 [63].

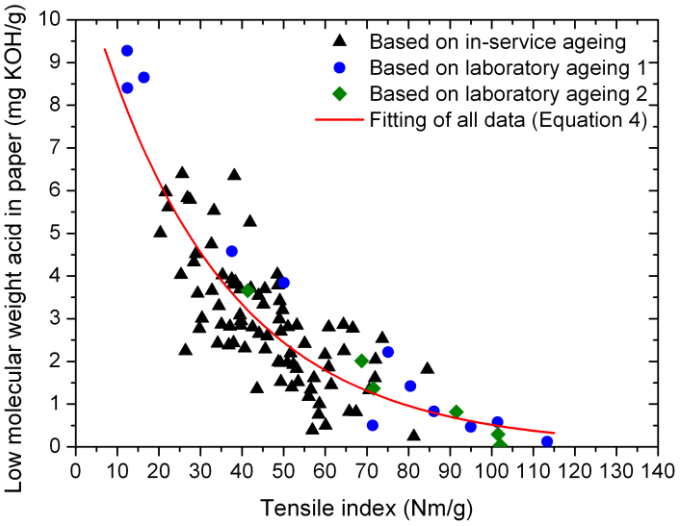


Figure 2-18 Relationship between TI and LMA in paper for in-service and laboratory ageing [63]

It was concluded from Figure 2-18 [63] that there exists a generic relationship between LMA in paper, which is independent of the ageing conditions. Due to the self-accelerated nature of the ageing process, this relationship between TI and LMA evolution presents itself as an exponential curve.

2) Water/Moisture

Oxidative degradation of the oil and hydrolysis of the paper both produce water. Thus, water measurement can be used as an indicator for ageing, on the condition that the moisture ingress into the system from the external environment is controlled. IEC 60814 provides the methodology for water content measurement in oil, which is based on coulometric Karl Fischer (KF) titration. A statistical plot for the moisture content in oil with transformer age is presented in Figure 2-19 [62].

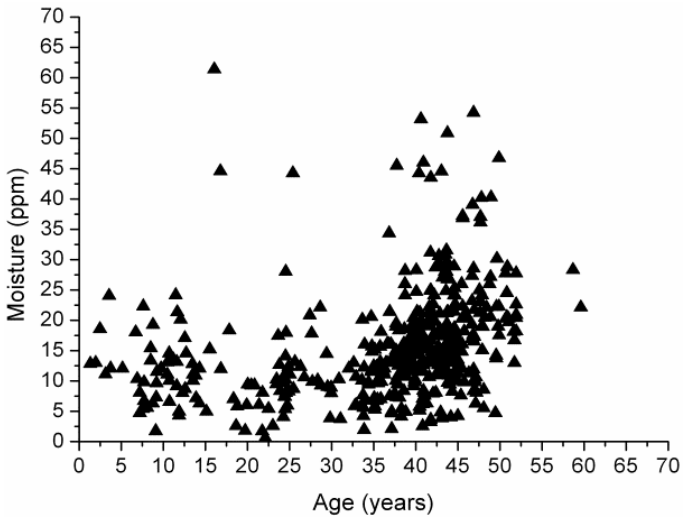


Figure 2-19 Moisture in oil vs transformer age [62]

Presence of high water content is detrimental to the system integrity by reducing the dielectric and mechanical strength of the insulation system, and also promotes ageing of the solid insulation. Ageing of oil also results in the increase of the saturation level of the oil, or its capacity to hold water, which can further promote ageing. Thus, a higher saturation level of oil may also indicate a more advanced state of ageing.

3) Furans

Furanic compounds are generated as a result of cellulose chain scission through either pyrolysis or hydrolysis/oxidation [26]. One of the primary products of paper ageing, furanic compound content can be monitored through oil. Figure 2-20 [64] shows the main furanic compounds from paper ageing which are 2-Furaldehyde (2FAL), 5-Hydroxymethyl-2-Furaldehyde (5HMF), 2-Furoic acid (2F), Furfuryl Alcohol (2FA), 5-Methyl-2-Furaldehyde (5MF) and 2-Acetyl Furan (2AF) [14, 38, 64]. ASTM D5837 provides the standard for measurement of furanic compounds by High-Performance Liquid Chromatography (HPLC).

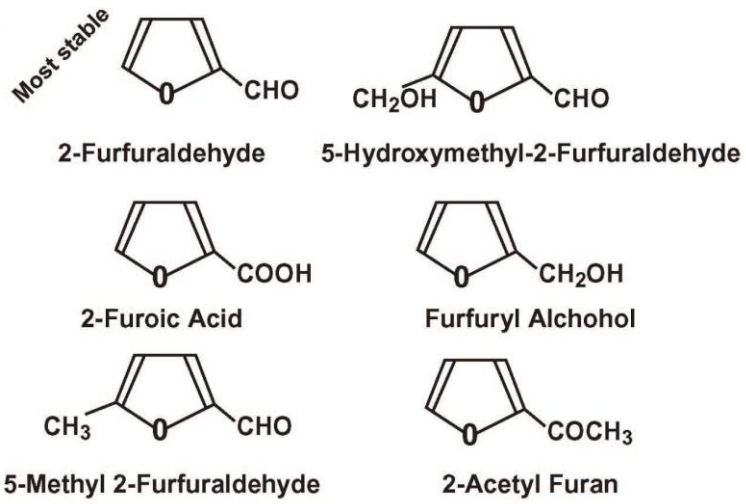


Figure 2-20 Furanic compounds generated as paper ageing products [64]

It is suggested that furanic compounds originate from hemicellulose, while other suggestions include glucose and levoglucosans [65]. Opening of the glucose rings through pyrolysis will result in the formation of levoglucosans, which in turn are decomposed into 5HMF, which results in 2FAL as a final product [65]. On the other hand, the formation of furanic compounds through hydrolysis/oxidation starts with the formation of hexose/glucose through hydrolysis of cellulose. Oxidation of glucose to pentose results in the formation of 2FAL as an end-product.

4) Methanol

Methanol was recently identified as an alternative indicator of paper ageing. It was proposed that methanol originated form the glycosidic scissioning of the cellulose chains [66]. Methanol production was demonstrated through ageing experiments conducted at temperatures ranging from 60 ℃ to 130 ℃, and controlling the initial water content in paper to 0.47%, 1.11% and 1.92% by weight [66]. A near-linear relationship between methanol production and chain scissions was observed, as illustrated in Figure 2-21 [66].

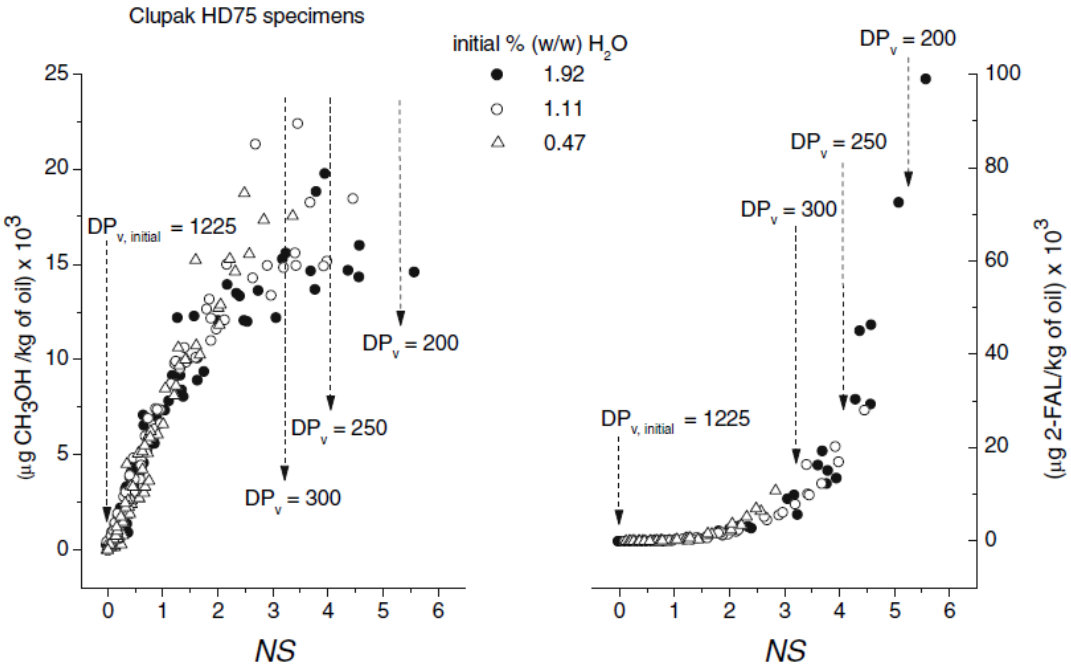


Figure 2-21 Relationship between (left) Methanol and chain scissions (NS) and (right) Furanic compounds and chain scissions (NS) [66]

From Figure 2-21 [66], it is clear that methanol measurements are more sensitive when compared to Furanic analysis when indicating early ageing of paper. Furanic compounds show a slow increase up to a DP value of 400 (number of chain scissions NS = 2), and then exponentially increase up to a DP of 200. This indicates that 2FAL measurements are less sensitive at a DP range from 1200 to 400, while methanol shows a linear increase up to a DP value of 400. Thus, it can be established that methanol is an effective early ageing indicator, when compared to 2FAL [66].

2.2.4.2 Physical and mechanical ageing indicators

1) Colour and appearance of oil

Colour and appearance can provide a quick means for comparison of oil samples, despite not being a critical ageing indicator. Oxidation of oil generates hydroperoxides which subsequently result in the darkening of the oil colour. Apart from this, other contaminants and degradation products can also affect the colour and appearance of the oil. Colour of the oil can be numerically expressed from 0.5 to 8.0 according to ISO 2049 [67]. A high colour number (which signifies a darker oil) could indicate a higher state of degradation. In terms of appearance, cloudy oil may be indicative of the presence of fibres, carbon, dirt, free water, sludge, or other

contaminants. For in-service transformers, inhibited oils usually have a lighter colour compared to uninhibited oils for the same service age and loading pattern [22].

2) Degree of Polymerisation (DP) of paper

DP is defined as the number of links in the long cellulose polymer chain. More specifically, it is the number of anhydro-β-glucose monomeric units in the cellulose polymer chain. The DP of new transformer paper after cellulose processing procedures is usually approximately 1000 [2, 23]. DP of paper can be measured using an Ubbelohde viscometer tube according to IEC 60450.

3) Tensile Strength (TS) of paper

Tensile strength is a mechanical property of the paper, indicating the paper's tolerance to exerted physical force until it breaks. Retained tensile strength is widely used for paper condition assessment, and can be converted to Tensile Index (TI) by dividing TS by the grammage of paper (g/m^2). TI of paper has been demonstrated to reduce with age, as shown in Figure 2-22 [63]. BS 1924 provides the standard for measurement of TI of paper.

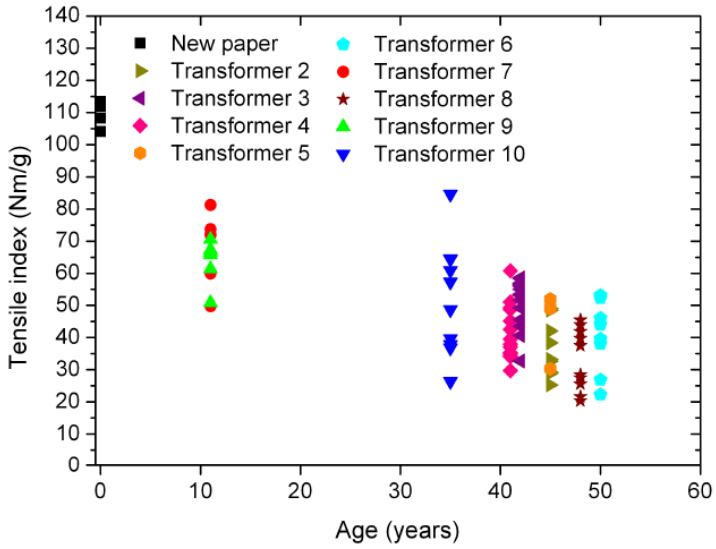


Figure 2-22 Relationship between TI and age of transformer for 9 transformers [63]

Owing to the folded geometry of paper in a transformer winding, DP is considered a more convenient parameter to describe the paper properties. A relationship between DP and TI has also been established, as illustrated in Figure 2-23 [15].

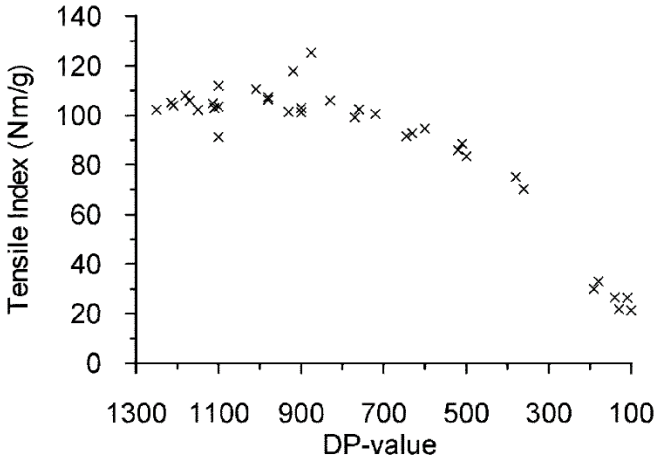


Figure 2-23 Relationship between TI and DP for Kraft paper [15]

2.3 Transformer Intervention Techniques

With a fleet of ageing transformers, power network operators rely greatly upon intervention techniques which can not only improving the asset performance but also contribute to reduced costs. Depending upon the size and criticality of location of the transformer in power network, system operators may opt for one or a combination of different intervention techniques available. The frequency at which this maintenance is done may vary between operators and the techniques used.

2.3.1 Oil and paper moisture dynamics

2.3.1.1 Moisture in oil

The aromatic components and impurities present in the oil attract more water [51]. Water can be absorbed in the form of hydrates by the polar ageing products of oil [51]. Moisture saturation curves for mineral oils were established. It was demonstrated that the saturation level of oil increases with temperature. Oxidation of oils through ageing results in the increase of polar ageing by-products, which would also lead to the increase of the saturation level of the oil. An example of this phenomenon is provided in IEC 60422, where the moisture solubility of an oil with TAN 0.3 mg KOH/g increased by a factor of two when compared with new oils. Comparison of moisture saturation levels in new and aged mineral oils over a temperature range of 20-80 ℃ is presented in Figure 2-24 [68].

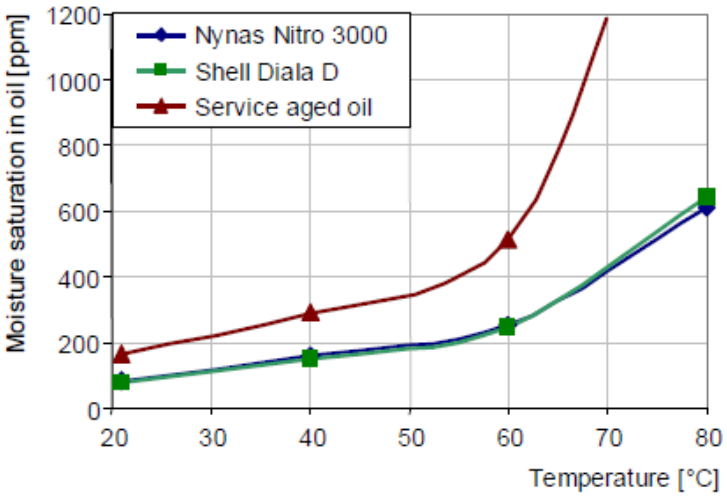


Figure 2-24 Moisture saturation level for new oils compared with 25 years service-aged oil [68]

It can be seen from Figure 2-24 [68] that the moisture saturation value for new mineral oils at 20 ℃ is around 55 ppm, while that for the aged oil is approximately 180 ppm. It was suggested that the increase in saturation level is greatly affected by the LMA content rather than the total acidity [51].

2.3.1.2 Moisture in paper

Moisture migration in cellulose occurs by diffusion through the porous structures and surface adsorption in the polar groups or active sites [69]. The polar groups activate the cellulose in attracting and adsorbing water molecules. Microcapillaries, which are small channels in the microstructure of the cellulose and cannot be oil impregnated, account for the adsorption of gas/vapour molecules. These gas/vapour molecules, given their electromagnetic attraction to the oppositely polar section of the active cellulose molecules, have limited mobility. However, occasionally, adsorbed molecules might break free and move through space till they are re-adsorbed. Other molecules then replace them in the previous site [51, 70]. Thus, the surface of the cellulose is under a dynamically changing state of equilibrium, further complicated by the presence of oil impregnation. From the above process, it can be inferred that the quantity of energy for de-sorption to occur is very high, and the process will be much slower due to physical barriers for the movement of the water molecules.

The effect of ageing on the Kraft paper's adsorption capabilities were discussed by Koch et al. [68]. It was observed that aged paper and pressboard exhibit reduced abilities to absorb moisture, as demonstrated in Figure 2-25 [68].

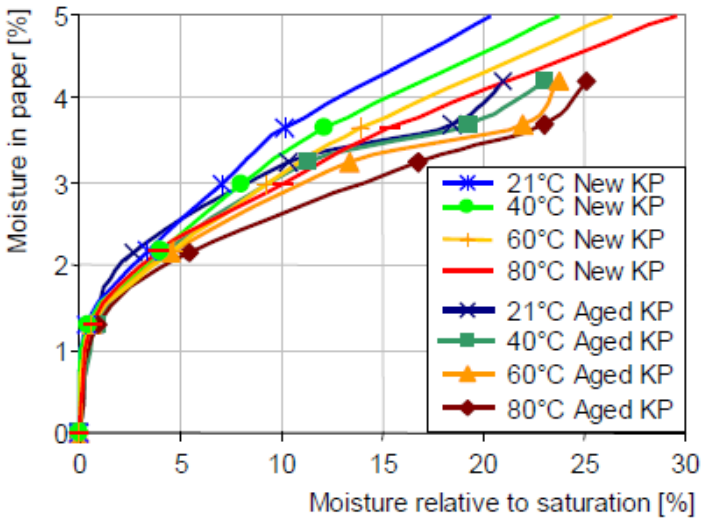


Figure 2-25 Moisture in new and aged Kraft paper at different temperatures [68]

Thus, it was established that ageing reduces the moisture adsorption capacity of paper, while it increases the saturation levels of oil. Hence, the migration of water between oil and paper will be different depending upon the ageing state and temperature of the system.

2.3.1.3 The oil-paper moisture equilibrium

It is irrefutable that the moisture in a sealed system is constant at a given point of time, discounting the increase in moisture due to the ageing of the oil and paper. This phenomenon can be represented as an oil-paper moisture equilibrium curve. Examining the transformer under equilibrium conditions is a quick way to study the moisture content in paper [42]. The most widely accepted moisture equilibrium curves were developed by Oommen in 1983, shown in Figure 2-26 [71]. The solid lines represent the adsorption curves (movement of moisture into cellulose) while the dashed curves denote desorption curves (diffusion of moisture out of cellulose).

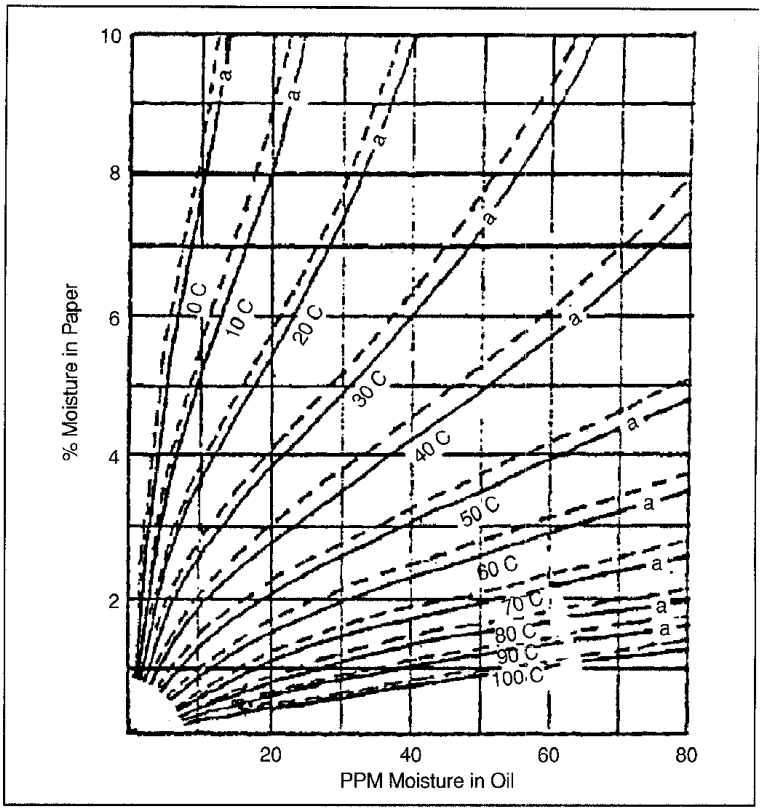


Figure 2-26 Oommen's curves for moisture equilibrium in an oil-paper system [71]

An increase in the oil temperature results in a reduction in the water content of the cellulose. This drives the water away from the conductor-wrapped insulation, which is heated intrinsically during the operation of the transformer. In addition, heating the oil drives the moisture from the bulk of the solid insulation into the oil [51].

2.3.1.4 Modelling of moisture diffusion into cellulose

The dynamic nature of the moisture equilibrium between oil and paper makes it very difficult to predict the exact moisture content of the solid insulation directly from the values of moisture in oil. Mathematical models are a powerful tool to investigate the moisture diffusion process. Finite Element Models (FEMs) [5, 6, 48, 53-55, 72-74] are most commonly used. The majority of these investigators, while utilising a common diffusion model, proposed different values/models for the moisture diffusion coefficient.

In order to simulate the diffusion process, a model based on Fick's second law can be assumed [75]

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D \cdot \frac{\partial c}{\partial x}\right] \tag{2-1}$$

where *c* is the local moisture concentration in the material (kraft paper), and *c (x, t)* is the local moisture concentration estimation along the sample thickness at each time instant. *D* is the moisture diffusion coefficient. A general model for the diffusion coefficient can be expressed by equation 2-2 [76, 77]

$$D(c,T) = D_0(T) \cdot e^{k \cdot c} \tag{2-2}$$

The above equation would be rendered non-linear due to the dependence of the diffusion coefficient of the cellulosic materials on moisture concentration. D_0 represents a pre-exponential factor which determines the temperature dependence of the diffusion coefficient, while *k* is a dimensionless parameter linking the moisture diffusion coefficient and the local moisture concentration. The boundary conditions of the model were proposed to be dependent on the sample temperature (*T*) and initial moisture content (C_0) [78].

$$C_{equi} = 2.173 \cdot 10^{-5} \cdot p_v^{0.6685} \cdot e^{\frac{4725.6}{T}} \tag{2-3}$$

where C_{equi} is the moisture in pressboard at equilibrium conditions (expressed in %), *T* is the temperature at the oil-pressboard interface, and p_v is the partial pressure of water vapour (in atm.). p_v can be calculated from the relative humidity of oil (RH), according to equation 2-4,

$$p_v = RH \cdot p_{vsat} = \frac{ppm}{ppm_{sat}} \cdot p_{vsat} \tag{2-4}$$

where *ppm* refers to the moisture concentration in oil, and ppm_{sat} and p_{vsat} refer to the moisture concentration and partial pressure (in atm) under saturation. The partial pressure of saturated water can, in turn, be obtained from equation 2-5, which was proposed by Foss [69].

$$\log(ppm_{sat}) = A - \frac{B}{T} \tag{2-5}$$

where A and B are constants whose values depend upon the type of oil involved, and whose values have been proposed by various authors, including Guidi and Fullerton [79].

p_{vsat} can be calculated according to equation 2-6,

$$p_{vsat} = \frac{p_c}{760} \cdot 10^{\left[\left(\frac{T_{ex}-T_c}{T_{ex}}\right)\cdot\left(\frac{a+b\cdot(T_c-T_{ex})+c\cdot(T_c-T_{ex})^3}{1+d\cdot(T_c-T_{ex})}\right)\right]} \qquad (2\text{-}6)$$

where:

p_c is the critical pressure (1.65807×10^5 mm Hg), T_c is the critical temperature (647.26 K) and *a, b, c and d* are constants, whose values have been proposed by Fessler as a: 3.244, b: 5.868×10^{-3}, c: 1.702×10^{-8}, and d: 2.188×10^{-3}. The above equations can be used to estimate the final moisture content in the paper in a given period of time for drying. The equation is dependent on the properties of the oil and paper in the system, apart from the system operating temperature.

2.3.2 Types of transformer intervention techniques

An efficient moisture removal from the oil impregnated paper/pressboard within a power transformer requires a combination of heat and vacuum [80]. Intervention techniques can be targeted at improving the condition of the transformer by improving both the oil and paper conditions. The various types of intervention techniques are oil purification, On-load Drying with Molecular Sieves (ODMS), adsorbent-based reclamation, Hot Oil Circulation (HOC), Hot Air Circulation (HAC), Vapour Phase Drying (VPD), Hot Oil Spray (HOS), and Low Frequency Heating (LFH).

2.3.2.1 Oil purification

Oil purification is the simplest form of 'reconditioning' the oil. It involves passing the oil through a filter element and removing all suspended particles and impurities in the oil. The level of purity achievable varies with the size and type of filter used. The oil is dried and degassed in the vacuum chamber at a temperature above the boiling point of water. This would ensure that all moisture from the oil is removed. A general sequence of this process is illustrated in Figure 2-27.

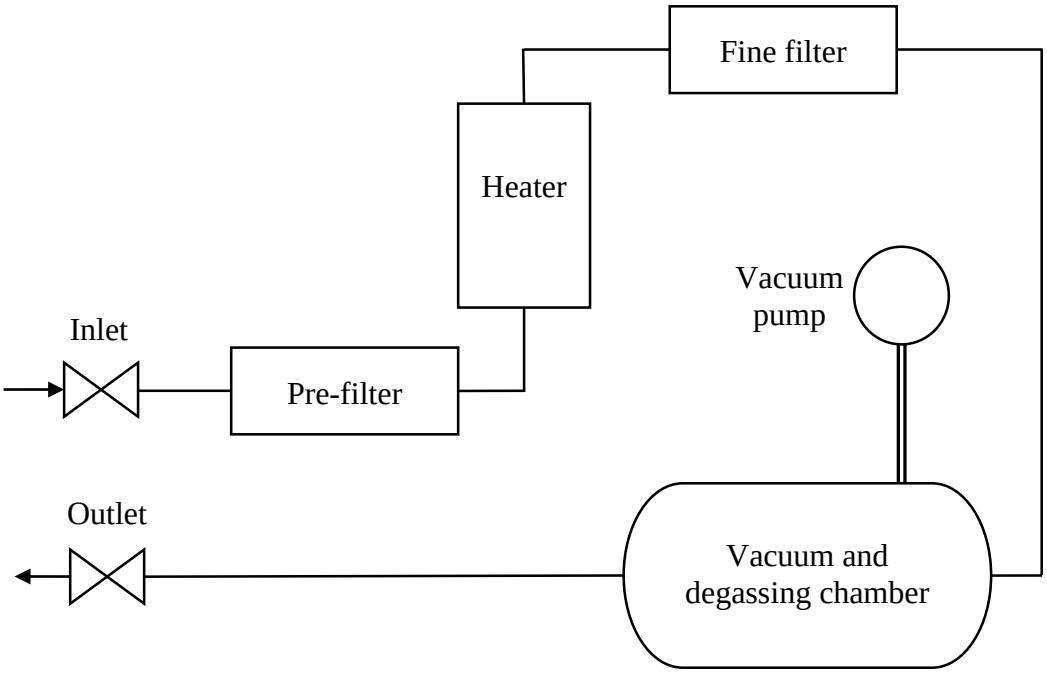


Figure 2-27 Flow diagram of a common oil purification unit

2.3.2.2 On-load Drying by Molecular Sieves (ODMS)

ODMS is a common technique which utilises several columns of molecular sieves for the absorption of moisture. Typical pore size of a molecular sieve such as Zeolite is 4 Angstrom [81], and molecules of a smaller size would be absorbed by the media. The molecular size of water is about 2 Angstrom, and would hence be absorbed.

The columns containing the molecular sieves are arranged in parallel and connected to the transformer in a separate compartment. The unit is operated when the transformer is on-load, and the removal of moisture occurs based on the principle of moisture equilibrium. The on-load temperature aids the migration of water from the paper into the oil, which is circulated at a slow rate (typically around 100 L/h) through the ODMS unit, where the water is removed. It is believed that this technique can remove up to 40% of the total weight of water from the transformer [82]. A typical ODMS unit is shown in Figure 2-28 [81].

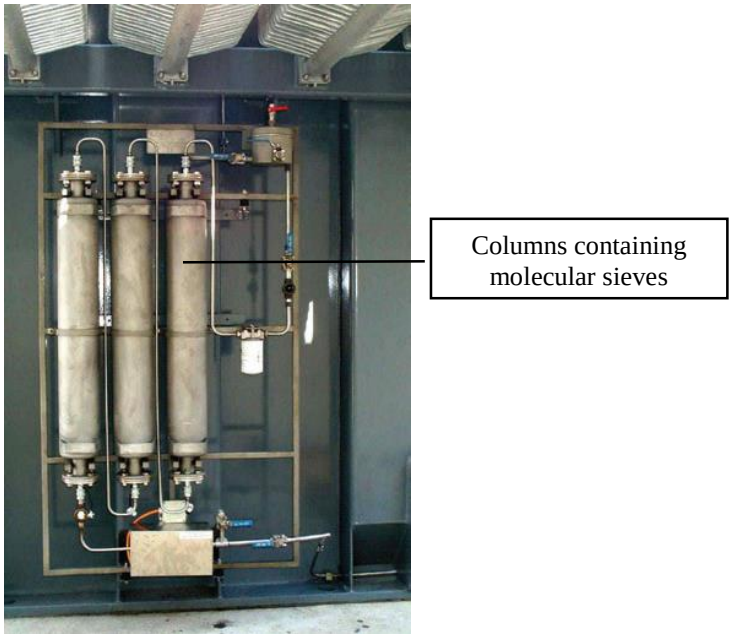


Figure 2-28 A typical ODMS unit [81]

While this technique is advantageous in terms of lower installation costs and less stress on the transformer insulation, the key disadvantage of this process is the slow speed of the drying, and the higher operational costs due to the expensive absorption units which need to be regularly replaced [83]. Furthermore, the oil needs to be re-inhibited post-processing due to loss of inhibitor content [83].

2.3.2.3 Adsorbent-based reclamation

Oil reclamation is similar to oil purification, with an additional stage to remove the acidic components and other degradation by-products from the oil. This stage utilizes an adsorbent bed (most commonly Fuller's earth or Alumina), which adsorbs the acids and other chemical ageing by-products from the oil, rendering the oil's properties comparable to that of new oil. This is so far the most extensive means of improving oil properties. Adsorbent-based reclamation could also remove the oxidation inhibitors from the oil, so it is necessary to re-inhibit the oil once this process is complete [84].

The reclamation process is essentially the same for both inhibited and uninhibited oils. The adsorbent 'clay' is a highly polar and granular material, made from natural bentonite, sepiolite or montmorillonite with a mix of metallic oxides. This material is 'activated' through thermal dehydration and partial dehydroxylation in order to increase its polarity, surface area and hence the catalytic activity. At the end of the

process, materials including acids, alcohols, aldehydes, ketones, esters, soaps and aromatic material (in case of uninhibited oil) are removed [84]. A qualitative comparison of oil subject to adsorbent-based reclamation is presented in Figure 2-29 [85].

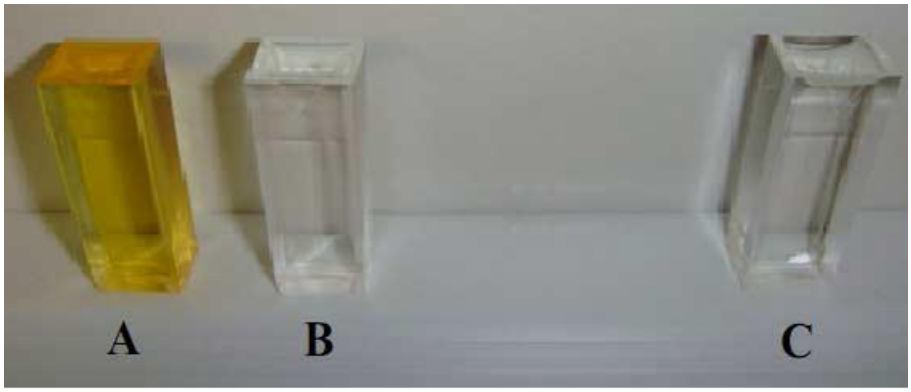


Figure 2-29 Qualitative comparison of oils subject to adsorbent-based reclamation; A: service aged oil, B: oil reclaimed after 15 passes and C: new oil used as reference [85]

It is, however, to be noted that the restoration of the oil properties does not necessarily mean that the service ageing of the transformer insulation will be reset to levels equivalent to that of a new transformer. Ageing of a transformer is primarily dependent on the age of the solid insulation, which is irreversible. Thus, existing ageing products of the solid insulation within the transformer could contribute to an accelerated ageing of the reclaimed oil, nonetheless at a slower rate when compared to the non-reclaimed oil. This ageing process can be further slowed down through addition of inhibitors and metallic passivators. However, a more significant reduction in the transformer ageing rate can only be achieved through the removal of the ageing by-products from paper.

Various natural and synthetic materials can be used for oil reclamation, and are presented in Table 2-1 [84]. Of these materials, fuller's earth and alumina are most commonly employed in the oil reclamation process due to high reusability and economic factors.

Table 2-1 Oil reclamation media [84]

Material	**Composition**	**Description**
Fuller's earth	SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, K_2O, TiO_2	• Naturally occurring clay • Contain both internal and external active polar sites, allowing retention of polar degradation components
Alumina/Bauxite	$Al_2O_3/Al(OH)_3$	• Hard durable • Higher reuse capability than clays • Fully dehydrated alumina the strongest sorbent medium
Silica, Kaolin, sand	SiO_2, clay, sharp sand	• Similar to Fuller's earth • Varying strength depending upon bauxite/silica content
Molecular sieves	Synthetic aluminium silicates, complexed metals	• Belong to zeolite class of materials • High affinity for polar components, particularly water • Significantly expensive than other materials
Carbonaceous	Derived from vegetable by-product charcoals	• Strong affinity for aromatic materials • May introduce unwanted foreign content into oil

2.3.2.4 Hot oil circulation

As the name suggests, this process aims at drying the solid insulation of the transformer through the circulation of hot oil. This process is conventionally accompanied either by oil purification or oil reclamation.

The oil treatment plant elevates the oil temperature to around 60-80 ℃, which is then circulated through the transformer tank. Usually, the tank is also evacuated using vacuum, so that the hot oil circulation will evaporate the water. Depending upon the

moisture content in the insulation, the size and the voltage level of the transformer, it might be necessary to repeat the heating cycle several times.

Drying times for HOC were calculated by Almendros-Ibaez et al. [6] based on simulations. The investigators utilised the drying model of a single strip of paper in contact with hot oil. By varying the thickness of the paper, the authors estimated subsequent drying times at different temperatures of oil. The authors provided additional insight into the drying process by varying the initial moisture content in the paper. They also provided drying time estimations for different insulation thicknesses with varying initial moisture in oil. From Figure 2-30 [86, 87] and Figure 2-31 [86, 87], an approximate drying time estimate for various thicknesses of paper can be obtained. Naturally, this estimate may not be completely applicable to a transformer system as several factors, such as environmental losses, along with presence of different thickness and types of paper in the system, play a major role in determining the drying time.

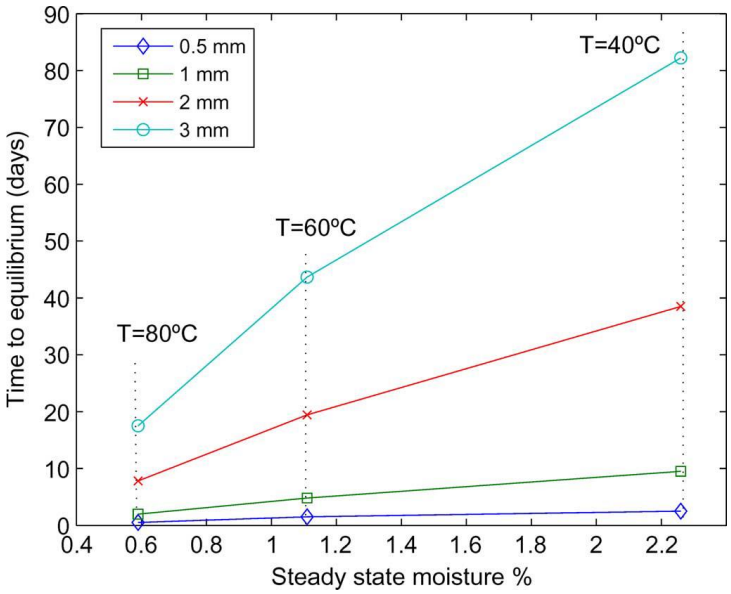


Figure 2-30 HOC drying times considering moisture in oil 10 ppm and initial moisture in paper 10% [86, 87]

Insulation thickness [mm]	Moisture in oil [ppm]	HOT OIL DRYING Temperature [°C] 40	60	80
0.5	10	2.5 days 2.26%	1.5 days 1.11%	0.5 days 0.59%
	20	1 days 3.59%	0.75 days 1.77%	0.42 days 0.93%
	30	0.5 days 4.70%	0.5 days 2.32%	0.29 days 1.23%
	40	0.18 days 5.70%	0.40 days 2.81%	0.25 days 1.49%
1	10	9.5 days 2.26%	4.79 days 1.11%	1.96 days 0.59%
	20	4.17 days 3.59%	2.96 days 1.77%	1.54 days 0.93%
	30	1.92 days 4.70%	2.04 days 2.32%	1.17 days 1.23%
	40	0.71 days 5.70%	1.50 days 2.81%	1 día 1.49%
2	10	38.5 days 2.26%	19.42 days 1.11%	7.8 days 0.59%
	20	16.67 days 3.59%	12.08 days 1.77%	6.13 days 0.93%
	30	7.75 days 4.70%	8.38 days 2.32%	4.96 days 1.23%
	40	2.83 days 5.70%	6.46 days 2.81%	3.96 days 1.49%
3	10	82.21 days 2.26%	43.67 days 1.11%	17.50 days 0.59%
	20	37.88 days 3.59%	27.33 days 1.77%	14.29 days 0.93%
	30	16.92 days 4.70%	18.96 days 2.32%	10.13 days 1.23%
	40	6.33 hours 5.70%	13.54 days 2.81%	8.88 days 1.49%

Figure 2-31 Drying time estimation for HOC [86, 87]

2.3.2.5 Hot air circulation

The oil os completely drained from the transformer tank, following which it is completely sealed and degassed. Hot air at a temperature of around 120 ℃ [88] is used to heat up the active parts of the transformer. Maximum insulation temperature is recommended at 105 ℃ [88]. The process is, however, inefficient due to the fact that it is impossible to completely evacuate and remove all oil from the tank. Further, the heating of active parts achieved by this process is non-uniform [88].

2.3.2.6 Vapour Phase Drying (VPD)

VPD is the standard drying process used during the production of large power transformers. This process relies on the evaporation of a solvent which is sprayed on the assembly to utilize the latent heat produced during its condensation [88]. Kerosene vapour is a commonly used heat carrier. The entire process is accomplished under vacuum, in a de-oxygenated atmosphere, which also helps reduce paper degradation during drying. While the VPD technology is extensively used in

transformer manufacturing factories, its on-site application has so far been limited. A typical installation of a VPD system on the field is shown in Figure 2-32 [89].

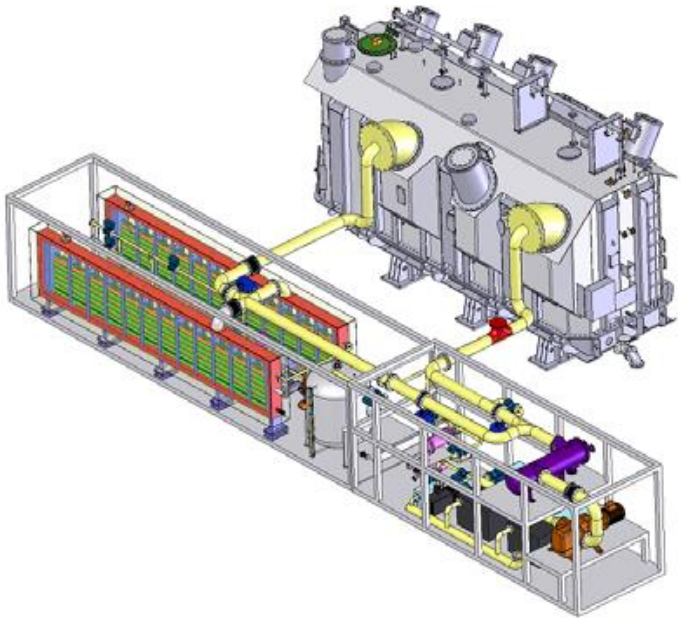


Figure 2-32 Typical field installation of VPD [89]

2.3.2.7 Hot Oil Spray (HOS)

Oil is drained from the transformer tank. Spray nozzles are then installed at the available flanges and hot oil is sprayed over the active part, along with the simultaneous application of vacuum. However, due to design of the core-type transformers, uniform heating of the entire transformer might be difficult owing to the presence of press-plates and shielding [90]. In case of shell-type transformers, this method is more easily applicable. The sprayed oil is collected from the bottom of the tank and is then reused after drying and degassing.

2.3.2.8 Low Frequency Heating (LFH)

Temperature and vacuum are two main factors for the drying speed and quality in a transformer. For a thorough drying, it is necessary that the transformer be heated along with simultaneous application of vacuum (as done in the vapour phase process). Utilising a low frequency reduces the short circuit impedance such a high current can flow through both windings at a low voltage.

Thus, through reduction of frequency in the LFH technique, the transformer is still functioning, but the voltages applied are far below the critical level [80, 91-93]. The lowered frequency current will result in the winding being heated thoroughly from

the inside, thus aiding in an efficient drying of the insulation. Modern LFH plants utilise the Dual Temperature Measuring and Heating (DTMH) system in order to separately determine the temperatures of the high and low voltage windings, as well as provide individual control over the heating of the two windings. Thus, higher drying temperatures can be used while avoiding hot spots and local overheating [80, 93]. While LFH is commonly utilised over the past during the production of distribution transformers, the utilisation of the same on larger power transformers has now become possible due to the introduction of the DTMH [80, 93]. The frequency used to heat the windings is in the range of 1 Hz [93]. A general layout of an industrially used LFH plant is presented in Figure 2-33 [93].

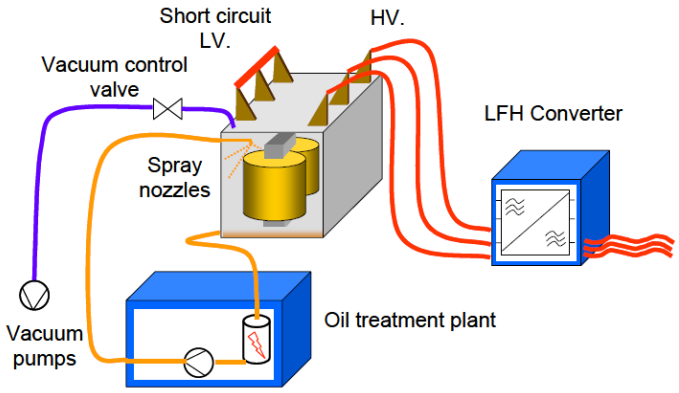


Figure 2-33 A mobile LFH plant configuration [93]

The key disadvantage of LFH is that only the paper on windings can be dried, while other materials like pressboard cannot be efficiently dried. The technology introduces a higher probability of having irreversible damages to the solid insulation due to high vacuum combined with temperatures, and a possible loss of clamping forces due to over-drying the cellulose. Further, LFH is an expensive technology due to high operating costs.

2.3.2.9 Comparison of solid insulation dry-out technologies

A comparison of the various dryout techniques based on water extraction per day is presented in Figure 2-34 [80]. It is to be noted that this comparison is solely based on the drying effect of the processes on the solid insulation. A better representation of this comparison should also account for economic aspects, portability and on-line feasibility of these technologies. From Figure 2-34, it can be seen that moisture removal through vapour phase drying is the quickest technology. This is followed by

LFH in combination with either HOS or HOC. HOC by itself still manages to remove about 3 L/day of moisture from the solid insulation.

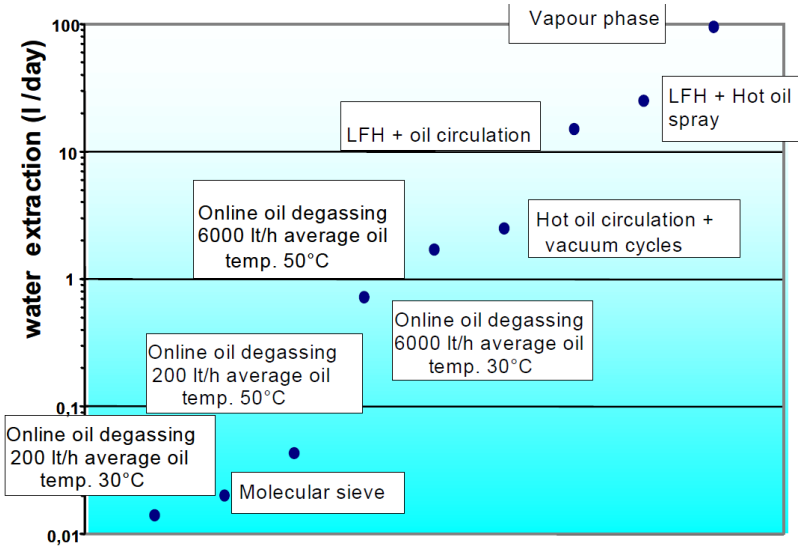


Figure 2-34 Moisture removal rate for a 400 MVA transformer with 14 ton insulation (from 3% to 1.5 %) [80]

2.3.3 Oil regeneration

IEC 60422 [94] defines oil reconditioning as 'a process that reduces physical contaminants by means of physical processes'. Reclamation is defined by IEC 60422 [94] as "*a process that eliminates or reduces soluble and insoluble polar contaminants from the oil by chemical and physical processing"*. Cigre [84] defines reclamation as "*the elimination of soluble and insoluble contaminants from an insulating liquid by chemical absorption means, in addition to mechanical means, in order to restore the properties as close as possible to the original values*". The term regeneration, reclamation and recycling are interchangeably used. In this thesis, the term 'reclamation' shall be used to signify the adsorbent-based process to purify oil, while 'regeneration' shall be used to describe the process which is a combination of Hot Oil Circulation (HOC) and FE-based reclamation. Hot oil is purified through a FE system, following which it is circulated through the transformer's tank. The cold oil is collected and repassed through the reclamation unit. This process is repeated for several days, or weeks depending upon the size of the transformer. At every circulation (termed as a step or cycle), the oil's intrinsic parameters like moisture, acidity and dielectric strength improve. It is believed that once the oil is completely reclaimed, continued recirculation through the transformer for extended periods of time will also remove the moisture and acidic by-products from the solid insulation to a certain extent [18]. This argument is based on the fact that equilibrium of

moisture and acids between oil and paper will start shifting to the oil, given that the oil is continuously flowing and the values of its chemical parameters such as moisture and acidity are very low.

Oil regeneration has the indubitable advantage that it can be performed both online and offline. This makes it a highly preferred maintenance practise for many power network operators, despite the availability of more efficient technologies, the majority of which can only be achieved offline. Oil regeneration can also be accomplished by Mobile Regeneration Units (MRUs). Figure 2-35 [95] illustrates the change in key ageing parameters with the number of circulations, for an on-site regeneration performed online.

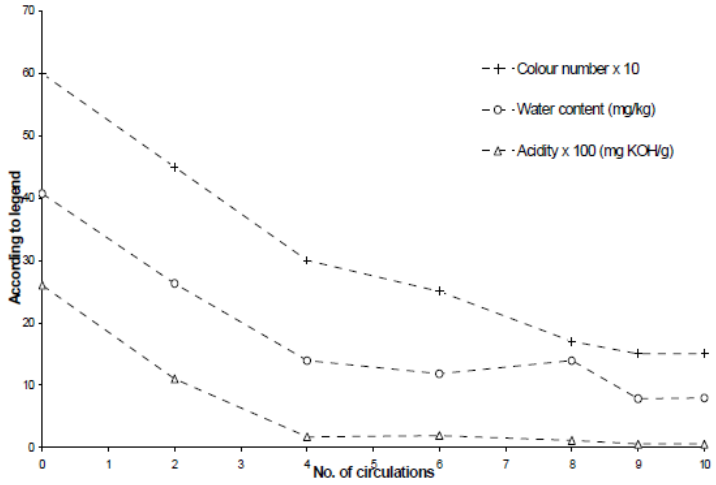


Figure 2-35 Acidity, colour and water content measured during on-line regeneration [95]

Regeneration commonly consists of two phases [96], a processing phase and a reactivation phase. In the processing phase, oil is reclaimed by forced percolation through the adsorbent system. It is then filtered, degassed before being returned back into the tank. Depending upon quality of oil, quantity of oil processed and the capacity of the regeneration unit, the duration of this process may vary. Once the adsorbent (in this case, Fuller's earth) is used to saturation, it needs to be 'reactivated' in order to restore its adsorbent capabilities. This may be done by backwashing the

Fuller's earth with certain chemicals or by a burning process. This process, termed as reactivation, could take up to 14 hours, again depending on the capacity of the unit.

In order to gain an overview of the oil regeneration systems, a list of some commercially available equipment is presented in Table 2-2.

Table 2-2 Overview of regeneration systems

	Provider A	**Provider B**	**Provider C**	**Provider D**	**Provider E**	**Provider F**	**Provider G**	**Provider H**
Plant Capacity (Regeneration Flow Rate)	2271 L/h	100k-300k L/month	around 2500 L/day (saturation in 6-8 hours)	1000-2000 L/h, 16000-20000 L/16 hrs (overnight reactivation of media)	2-3 weeks to completely purify 40 Tons of highly aged Oil	360k-1440k L for 8-12 cycles	5000 L/day	2500 L/h
Filter size (micro m)	0.5	0.5	1	0.2		1	0.5	5
Final Residual moisture			<= 5 ppm	<= 5 ppm	< 10 ppm	<= 5 ppm	< 4-8 ppm	<= 5 ppm (3 passes)
Operating temperature (℃)	20-120		80	65	50-70, Energy Re-use	50-80		60-70
Final Acidity mg KOH/g		< 0.03	< 0.01		< 0.01	0.01		< 0.03
Other Notes	Vacuum chamber, Optional FE treatment, Mobile Option	Reactivation, Optional Oil purifier (apart from FE)	Mobile service, Bauxite media	Offline, FE media	Mobile only, Re-inhibition	Stationary and Mobile Option, FE media	Mobile, FE media	Vacuum oil Treatment, Re-inhibition, FE and Aluminium Oxide mix media

2.4 Case Studies of Transformer Insulation Reconditioning

Several studies have been conducted in the past to investigate the oil and paper re-conditioning techniques, through on-site application or laboratory experimentation. In order to gain an understanding of the effects of the various transformer insulation reconditioning techniques, a case study analysis of the same has been undertaken.

2.4.1 Case 1 – Drying of a 45/15 kV, 5 MVA power transformer through vacuum drying and Hot Oil Circulation (HOC)

Garcia et al [5] studied the drying of solid insulation through vacuum drying followed by HOC in order to verify the drying models previously proposed by them. The transformer under test was a retired 45/15 kV 5 MVA transformer manufactured in 1967. The investigators installed optical sensors on the windings in order to monitor the temperature evolution during the drying process, in locations as seen in Figure 2-36 [5].

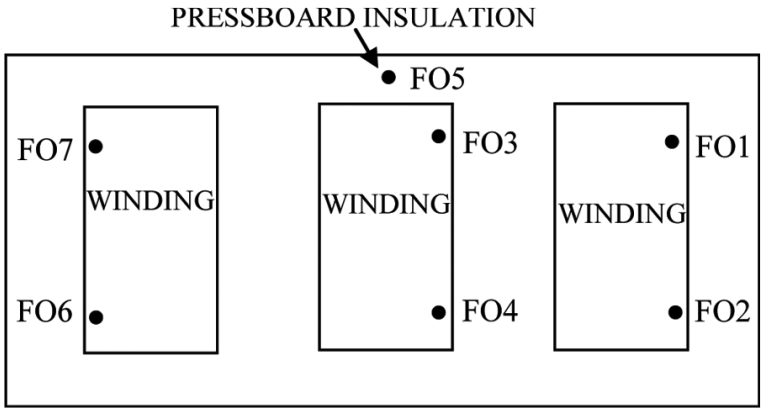


Figure 2-36 Locations of optical fibres installation for 5 MVA transformer [5]

The active part of the transformer was exposed to ambient conditions for 8 days in order to achieve high levels of moisture in paper. This was followed by the drying process in two stages – the initial stage being vacuum drying and the second stage being hot oil circulation. Drying under vacuum was accomplished by draining the transformer tank and applying a 1 mbar vacuum at ambient temperature for a period of 24 hours, during which the oil was degassed and dried separately. This was followed by the hot oil circulation at 60-65 ℃ for a further period of 24 hours. The temperature profile for the entire process is presented in Figure 2-37 [5].

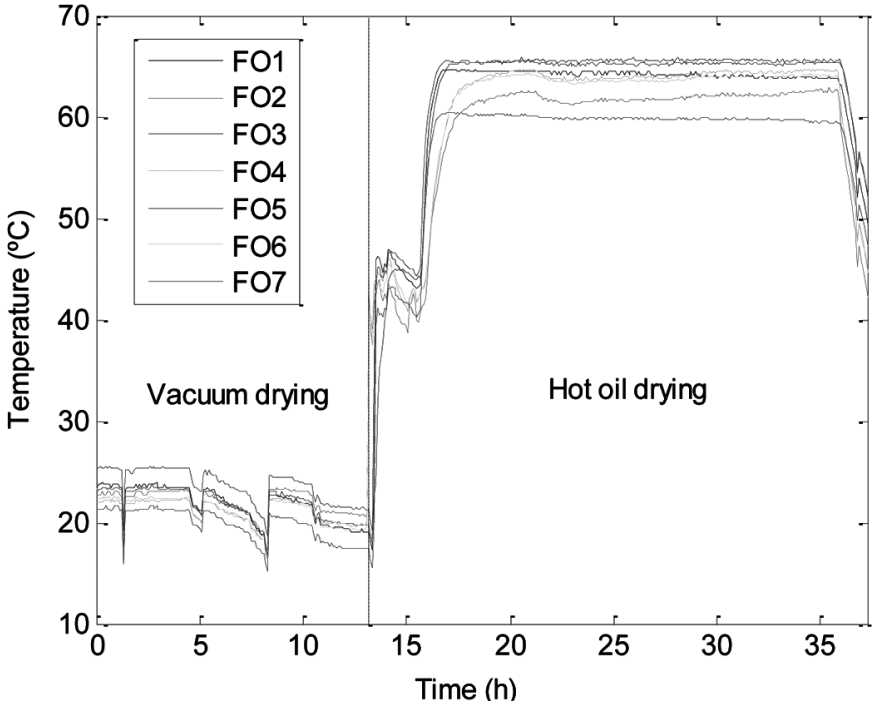


Figure 2-37 Temperature during the drying process for 5,000 kVA transformer [5]

Insulation samples were collected before and after the process in order to compare the drying effect. Moisture was measured through Karl-Fischer titration, the findings of which are provided in Table 2-3 [5]. The moisture content in paper samples obtained from the conductors were found to be reduced by approximately 70%, while the samples from the pressboard barrier exhibited a reduction in moisture of nearly 43%.

Table 2-3 Moisture content before and after drying 5,000 kVA transformer [5]

Sample	Moisture before drying (%)	Moisture after drying (%)
Conductor	**7.55**	**2.20**
Pressboard barrier	**2.17**	**1.24**

The investigators concluded that there is a good correlation between the proposed drying models and the obtained results from the experiment. It was highlighted that the application of vacuum does not have any effect on the process if the insulation temperature remains low, and that energization of the transformer may be necessary in order to achieve a higher temperature. Finally, it was suggested that the thermal isolation of the transformer is crucial in order to avoid environmental heat losses.

2.4.2 Case 2 – Field-drying of a 93 MVA power transformer using Hot Oil Spray (HOS)

Foss et al. [69] analysed the field drying of a new 93 MVA transformer through the installation of multi-layered paper samples in the transformer before its commissioning. The investigators installed thermocouples in various locations of the transformer to study the temperature distribution during the vacuum HOS procedure used for the solid insulation dryout. Paper models comprising of 50 layers of paper were installed in four different locations to monitor the moisture ingress. The position of the paper models and thermocouples are shown in Figure 2-38 [69].

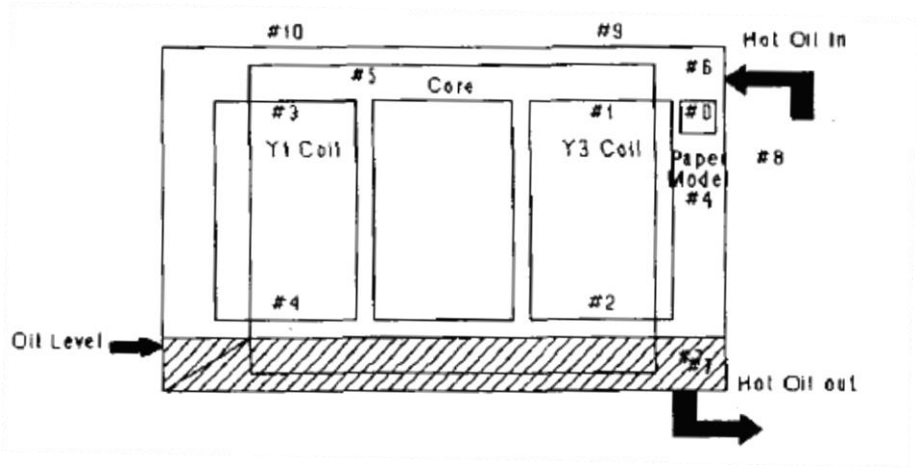


Figure 2-38 Thermal sensors installed prior to dryout of the 93 MVA transformer [69]. The position of paper model 4 is also shown below thermocouple #0

Hot oil spray at 80 ℃ was circulated from the top of one phase, and the oil outlet was located near the bottom of the same phase. The four models were removed at different times ranging from factory assembly to post-dryout, in order to represent different conditions as elaborated in Table 2-4 [69].

Table 2-4 Conditions represented by the different samples in Foss et al.'s study [69]

Model number	Condition represented
1	Moisture content in insulation after inspection
2	Moisture content of insulation prior to installation
3	Moisture content prior to vacuum dryout
4	Moisture content at the end of the drying operation

The first three paper models present an increasing moisture profile from the outer layer to the inner layer. For the paper in model 3, moisture was 2.43% for the outermost layer and 0.62% for the innermost layer before the dryout process.

During the dryout, the investigators reported a maximum temperature at sensors 0 and 6 (around 80 ℃), while sensors 7 and 2 indicated temperatures in the regions of 70 ℃. Sensor 1 indicated lower temperatures, only reaching a maximum of 50 ℃, as was the case with sensor 4. The other sensors indicated extremely low temperatures ranging from 10 ℃ to 20 ℃, signifying the uneven distribution of the temperature despite the oil not being circulated through the radiators.

After a processing time of 210 hours, the moisture content in the outermost layer of the paper model 4 reduced from 2.43% (model 3) to 0.96%, indicating a 60% reduction in moisture levels. Moisture in the innermost layer of paper remained unchanged.

2.4.3 Case 3 – Comparison of field drying of transformers by molecular sieves and cellulose cartridge filters

In a field study comparison of two different dryout techniques, Nick Lelekakis et al. [97] presented moisture reduction trends when a transformer was dried using molecular sieves and another using cellulose cartridge filters. The transformers under test were two identical free-breathing 49 year-old transformers. The investigators presented the oil temperature profile during the dryout for both transformers, labelled Tr1 and Tr2, where Tr1 was subject to drying using cellulose cartridges, while molecular sieves were utilised in the drying of Tr2. It was noted that the top of the transformer is generally hotter than the bottom. They then proceeded to present oil moisture profile of both transformers for the approximately 6 month dryout period, obtained from moisture probes installed at the dryer inlet and outlet of each transformer. A flow meter was used to monitor the flow rate of the oil (Q) in litres per hour, and the total water removed (in litres) was calculated as

$$total\ water\ removed\ (L) = \sum \left[\frac{PPM_{in} - PPM_{out}}{10^6} \cdot Q \right] \quad (2\text{-}7)$$

where PPM_{in} is the hourly average water content of the oil (ppm) at the inlet of the dryer, while PPM_{out} represents that at the outlet of the dryer. The summation extends over the total drying time (hours). The oil in the transformers was known to be of Nynas 10GBN brand, which is an uninhibited mineral oil. The moisture in oil profile for these transformers are presented in Figure 2-39 and Figure 2-40 [97].

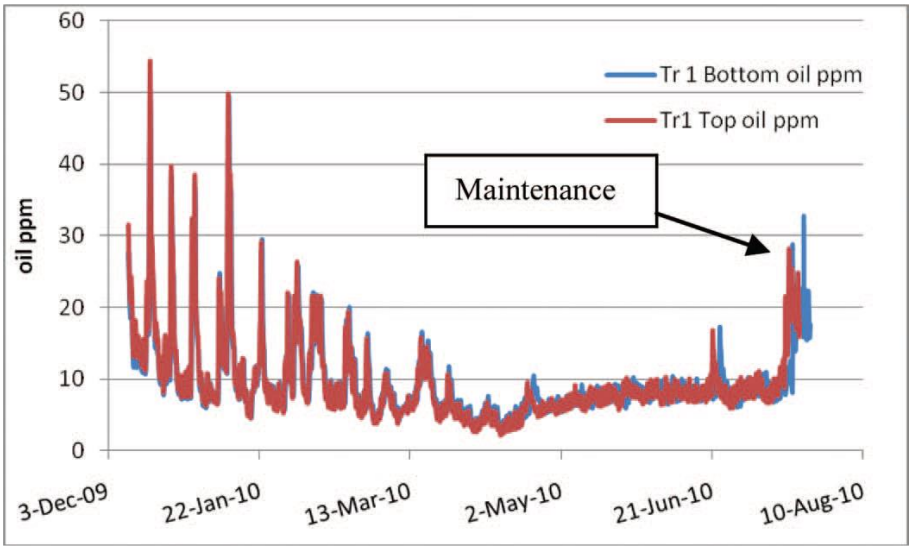


Figure 2-39 Water content of the oil for Tr1, drying using cellulose cartridge filters [97]

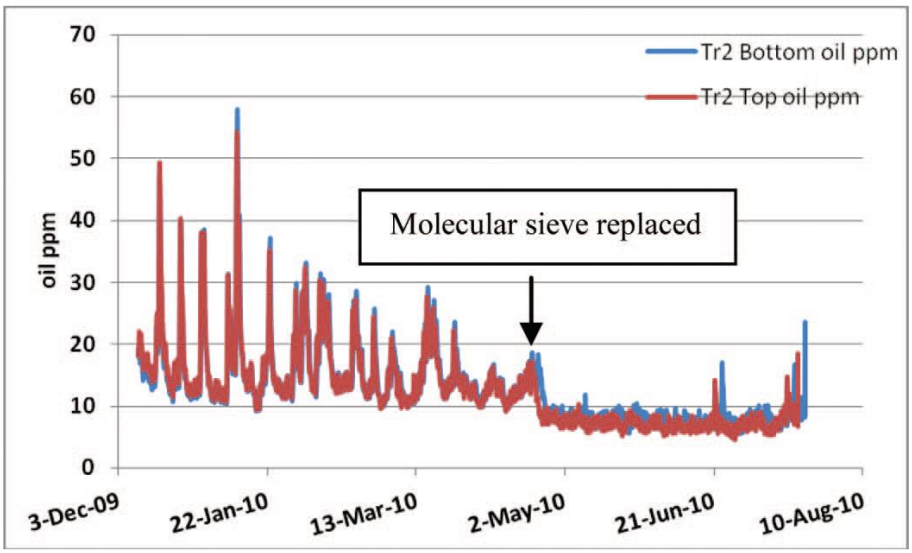


Figure 2-40 Water content of the oil for Tr2, drying using molecular sieves [97]

It was reported that a total of 12 L of water was collected from the cellulose filters for Tr1. Using the change in weight of the molecular sieves before and after dryout, it was estimated that a minimum of 6 L of water would have been removed by the molecular sieves. It was estimated from equation (2-7) that approximately 7.5 litres of water was removed from the transformer over the period of approximately 6 months using the molecular sieves from Tr2. The difference is attributed to the different flow rates, i.e., 1041 L/h for the cellulose cartridges and 141 L/h for the molecular sieves.

Water content in paper was estimated by the investigators through three different methods – the first through water activity of the transformer oil, second through

dielectric response, and the third by direct measurement using Karl-Fischer titration of the paper samples collected from Tr2 after the dryout. These results of moisture measurements are presented in Table 2-5 [97].

Table 2-5 Water content in paper (%) estimated by three methods [97]

Item	**Transformer**	**Date**	**Moisture in oil estimated by – (ppm)**		
			Water activity of the transformer oil (top/bottom)	**Dielectric response method**	**Karl Fischer (direct measurement)**
Before dry-out	Tr1*	29 Oct 2009	4.0/6.0	5.1	NA
	Tr2**	12 Dec 2009	4.0/6.3	5.4	NA
After dry-out	Tr1*	8 May 2010	2.1/4.0	4.3	NA
	Tr2**	8 May 2010	2.4/4.5	3.6	NA
		2 Aug 2010			4.3 (bottom)
*Tr1 = transformer 1; **Tr2 = transformer 2					

It was noted that an approximate reduction in moisture in paper of 30% is reported in both transformers, with the KF measurement results conforming to the estimated value through water activity of transformer oil. The investigators concluded that the molecular sieve method, which requires regular replacement with saturation, is less suitable for drying a wet transformer when compared with cartridge filters, which need less frequent replacement.

2.4.4 Case 4 – Study of long-term performance of transformer after on-site oil regeneration with and without inhibition post-regeneration

In a study of on-site oil regeneration, Koestinger and Bruarøy [93] reported the long-term performance of transformers which have undergone oil regeneration in comparison with those where the oil was completely replaced. In case of oil regeneration, the inhibitor content was re-established after reclamation. They also presented a comparison of the transformers where regeneration was performed with a limited amount of adsorbent, which would affect the efficiency of the process.

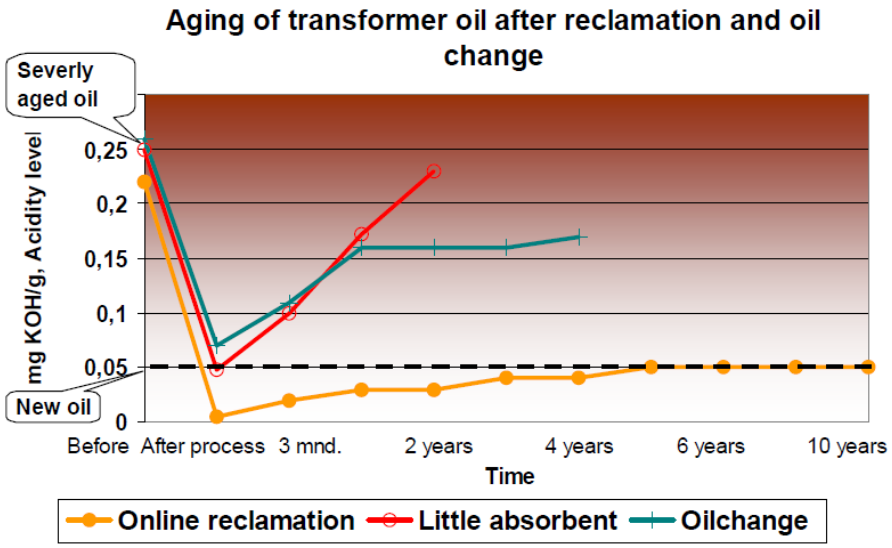


Figure 2-41 Long-term evolution of acidity in transformers after reclamation and oil replacement [93]

From Figure 2-41 [93], it is clear that the long-term performance of the transformer which had undergone on-line oil reclamation is significantly better than the transformer where oil replacement was carried out or little adsorbent was used. The values of acidity remained under 0.05 mg KOH/g after 10 years for the oil reclamation case, in comparison to around 0.16 mg KOH/g within 4 years for the oil replacement case. While this trend is a definitive indication of the better performance of the transformer after oil regeneration and re-inhibition, the performance without re-inhibition has not been reported.

2.4.5 Case 5 – Study of on-line oil regeneration on a power transformer

An on-line regeneration process was performed on a power transformer using a mobile regeneration unit [98]. A 3-day oil regeneration service was performed using 15 columns of Bauxite beds for 7000 litres of oil contained by the transformer. The mobile regeneration unit consisted of two separate parts, one for reconditioning (removing solid contaminants, water, and dissolved gasses) and another for regeneration through the adsorbent media.

The oil was reconditioned by putting it through the drying cycle for 24 hours, following which it was passed through the 15 columns of bauxite beds in order to remove the oxidation products. It was reported that the beds of adsorbent were saturated after 6-8 hours of regeneration, or after an equivalent oil volume of 18,000-25,000 litres had passed through it. Reactivation was performed overnight, during

which the normal reconditioning process continued. The oil test results for the regeneration process are presented in Table 2-6 [98].

Table 2-6 Oil test report for on-site regeneration by EOS [98]

Day count	Acidity	Number of reactivations / passes
1	0.3145	Original value
1	0.009	1 / 3 passes
2	0.008	2 / 36 passes
2	0.009	2 / 6 passes and addition of 0.5% inhibitor

The final result indicated significant improvements to the acidity, with a value similar to that of new oils. Similar improvements in other parameters including Interfacial Tension (IFT), Dielectric Dissipation Factor (DDF) and Resistivity were also reported. Inhibitor of 0.54% was re-established post-regeneration in order to achieve 'as new' oxidative stability of the oil. Oil water content was also reported to be reduced from an initial value of 49 ppm to 5 ppm. The service provider inferred from the slow rate of reduction of moisture in oil that some moisture from the surface/outer layers of the paper insulation could have been removed. They also noted that the oil condition would remain below the test limits for unused mineral oil as specified in IEC60296:2012 for a further 15 years given the re-inhibition operation. While they commented that there will be no restoration to previous degradation of paper strength, they stated that the regeneration process would aid in limiting further degradation provided regular monitoring of the inhibitor content.

2.4.6 Case 6 – Investigation into the post-maintenance failure of 156/22 kV, 375 MVA power transformer

In a case study reported by TJH2b during the 2012 S-12 Taskforce meeting [99], the post-maintenance failure of a 156/22 kV, 375 MVA, 40 year-old transformer was analysed. Maintenance in the form of oil processing was performed after furan analysis indicated aged insulation. While on-line moisture monitoring was not commissioned during the maintenance operation, three days of data obtained near the end of the procedure indicated a significantly high relative saturation value of the top oil moisture (in the range of 40% at sensor temperatures of around 30-35 ℃). This is contradictory to the expected dry condition of the oil post-processing. However, judging by the fact that the %RS value was still below the value of 50% as suggested by the IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment (c57.106) [100], the transformer was gradually re-energized. This decision was

further backed by the recommendation by C57.106 to not try to evaluate moisture in paper through moisture in oil. However, the transformer soon failed during the start-up, when the load was at 0.5pu. Post-failure investigation through the use of saturation curve and measure moisture content in oil indicated a moisture content in paper in the range of 8% to 9% post-processing (drying) of the oil. It was concluded that the moisture level in oil was below the equilibrium, and oil processing/drying did not solve the issue of the dripping wet paper insulation. These results were confirmed through laboratory measurements of moisture in paper. Further investigations also indicated a leak in the bushing gasket, allowing the ingress of rain water into the paper below the bushings. During the post-maintenance start-up, bubbles were formed due to excessive moisture in the paper at the top of the winding, which led to arcing and subsequent breakdown and failure.

2.4.7 Case 7 – Laboratory investigations into the drying of 31.5 MVA transformer using a combination of LFH and HOC

Leibfried et al. [101] provided data from LFH combined with HOC on a 31.5 MVA transformer, conducted for a duration of 250 hours at a temperature range of 100-110 ℃ and 2 mbar vacuum pressure. The water extracted from the windings during the drying procedure was titrated, and the acid content measured was considered to represent LMA extracted by the process. The trend, presented in Figure 2-42 [101], shows that LMA extracted from the system reduces up to a certain point, beyond which the amount of acid extracted increases. This signifies that initially, acidic substances from the oil is removed. Once the oil is substantially ‘pure’, acids from the solid insulation start migrating into the oil, enabling its removal. The investigators also noted that the DP of the paper did not change after the drying procedure, and concluded that the process does not result in any significant ageing or damage to the solid insulation.

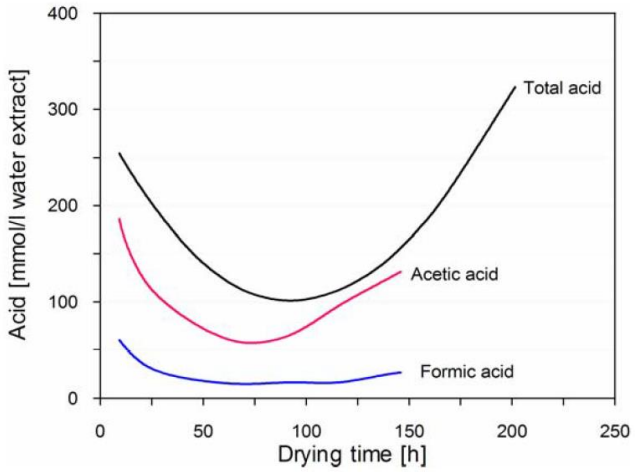


Figure 2-42 LMA extraction profile during LFH [101]

2.5 Summary

The life of a transformer is commonly defined by the life of the solid insulation (paper and pressboard) present in the transformer. The ageing of paper and oil produces many by-products including moisture, acids, gases and furanic compounds. Through dissociation of some of these acids, such as LMA, the hydrogen ions produced result in a self-catalysed reaction to contribute to further degradation of paper through hydrolysis.

The ageing of paper and oil can be monitored by measuring the by-products produced. Most commonly, acidity, furanic content and gases are used to speculate the age of the oil/paper. Recently, methanol has also been found to be an early ageing indicator of paper. In this thesis, the ageing assessment of oil is made through acidity and moisture measurements, while that of paper is made through TI, LMA and moisture measurements.

Various technologies are available for reconditioning the transformer insulation. Most of these technologies are only feasible offline, given the need to evacuate the entire tank of oil. However, network operators prefer on-line treatments to avoid electricity supply interruption.

Hot Oil Circulation (HOC) is the only one which can be accomplished online in a cost-effective yet considerably efficient way. Due to the promising effects of utilising HOC in combination with fuller's earth reclamation in improving paper conditions,

the drying of transformer insulation through oil regeneration is discussed. There is limited evidence available to show the improvement of paper conditions in the transformer through oil regeneration. Thus, the effect of this process is analysed in this work through oil regeneration experiment conducted on a 77-year-old retired distribution transformer.

Chapter 3. Ageing Assessment of Regenerated Oil

3.1 Introduction

This chapter aims to address the question of the long-term effects of oil regeneration on the insulation system through laboratory ageing experiment. The ageing experiment aims to compare the ageing characteristics of oil before and after being subject to regeneration process. Various new oils were also tested as a benchmark. Regenerated oil samples obtained from a previous study [7] were utilised in this investigation. Laboratory accelerated thermal ageing experiments were performed on these samples alongside new inhibited and uninhibited mineral oil samples. The key oil ageing parameters, namely Total Acid Number (TAN), moisture, Low Molecular weight Acids (LMA), and High Molecular weight Acids (HMA), and paper ageing parameters including moisture, Low Molecular weight Acids (LMA) and Tensile Strength (TS) were analysed and compared among the different oils.

The non-regenerated and regenerated samples of oil were obtained from a previous study which consisted of on-site oil regeneration performed on an in-service transformer [7]. The transformer under study was a 44-year-old 132/33 kV transformer used in a distribution network. On-load and off-load oil regenerations were performed on this transformer. A connection schematic of the setup used for the study is presented in Figure 3-1 [7].

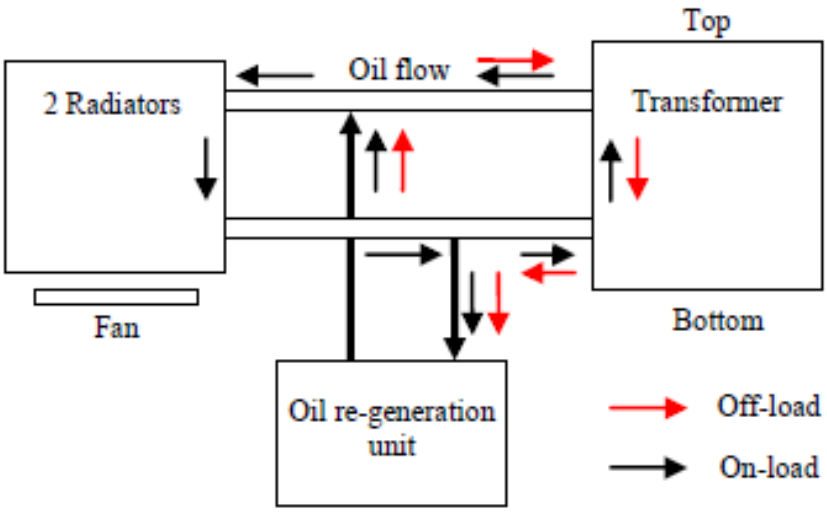


Figure 3-1 Connection schematic for the oil regeneration performed on 132/33 kV transformer [7]

In the study, off-load oil regeneration was carried out with the aim of cleaning/re-conditioning the oil, followed by on-load regeneration with the aim of improving the condition of the paper through the removal of moisture and acidic by-products of ageing. A total of 8 regeneration cycles were carried out in between 8 reactivation cycles meant to reactivate the column containing the regeneration media. Oil samples were collected every 2 hours on average during the regeneration. The operating sequence for this process is shown in Figure 3-2 [7].

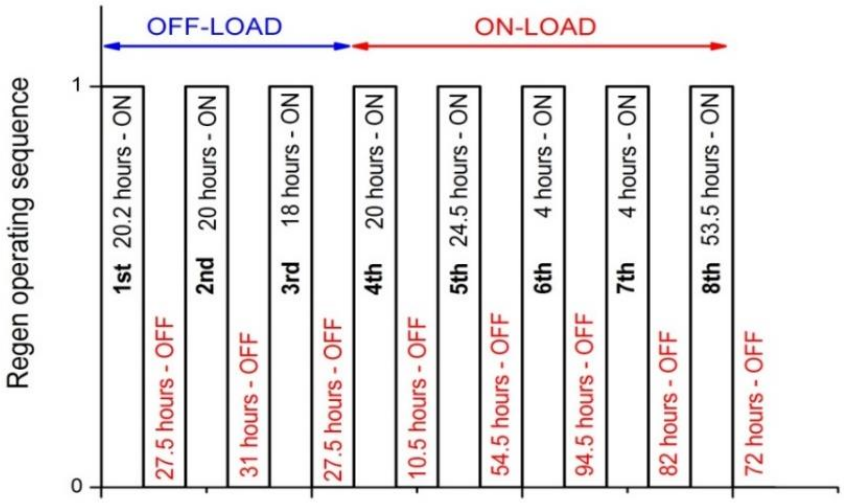


Figure 3-2 Operating sequence for oil regeneration process on 132/33 kV transformer [7]

The obtained profile for TAN of oil is presented in Figure 3-3 [7], and the change in colour of the oil through the oil regeneration is presented in Figure 3-4 [7]. Profile of the acidity of oil indicated a reduction of TAN from approximately 0.2 mg KOH/g to a value of around 0.008 mg KOH/g during the first (off-load) stage of the regeneration process. TAN of the oil was found to fluctuate during the second (on-load) stage of the regeneration process, which was attributed by the investigators to the flushing of acidic by-products from the paper insulation. Oil colour was observed to change from a dark amber to clear and transparent, similar to that of new oils.

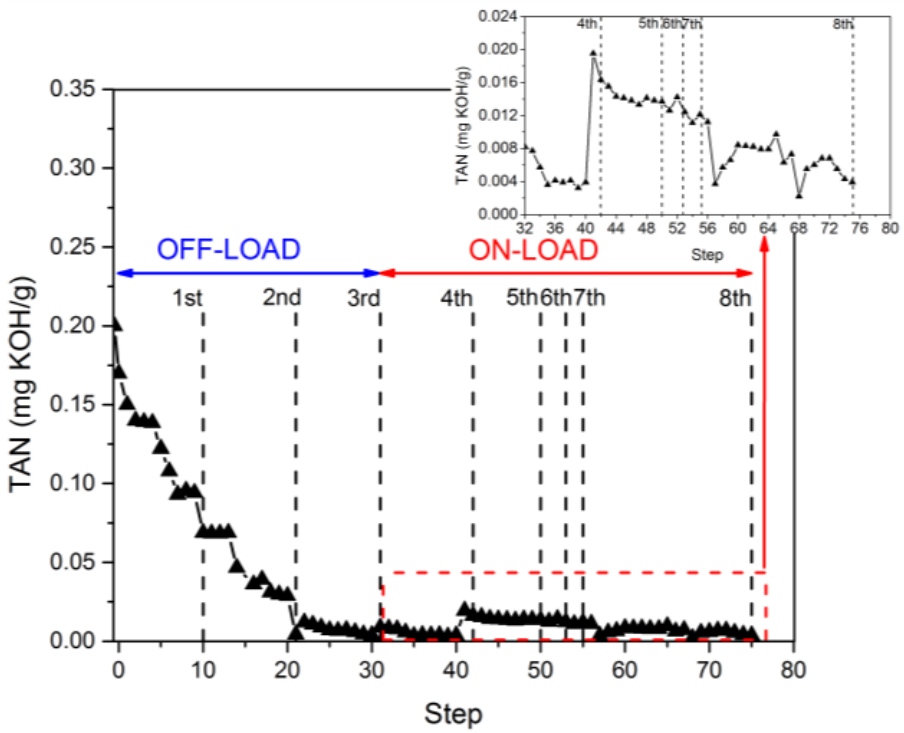


Figure 3-3 TAN of oil profile during off-load and on-load oil regeneration of 132/33 kV transformer [7]

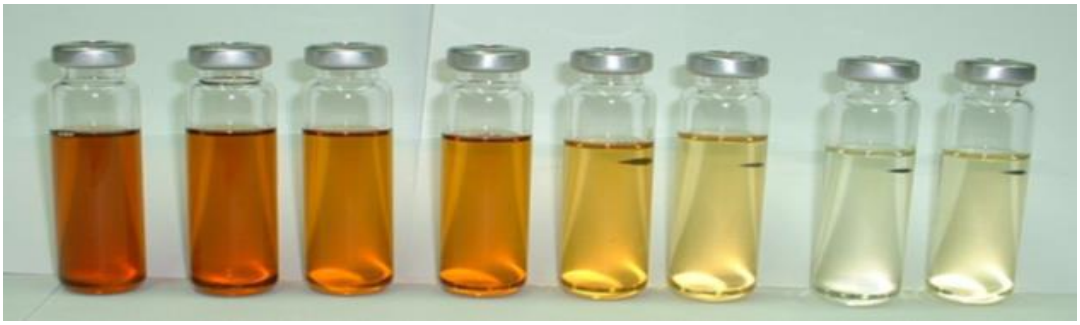


Figure 3-4 Colour change of the oil samples from (left) before oil regeneration to (right) after regeneration for 132/33 kV transformer [7]

The profile for oil moisture during the regeneration procedure is presented in Figure 3-5 [7]. Initial moisture in oil was reported at 18 ppm, which fluctuated during the entire procedure, finally settling at around 10 ppm.

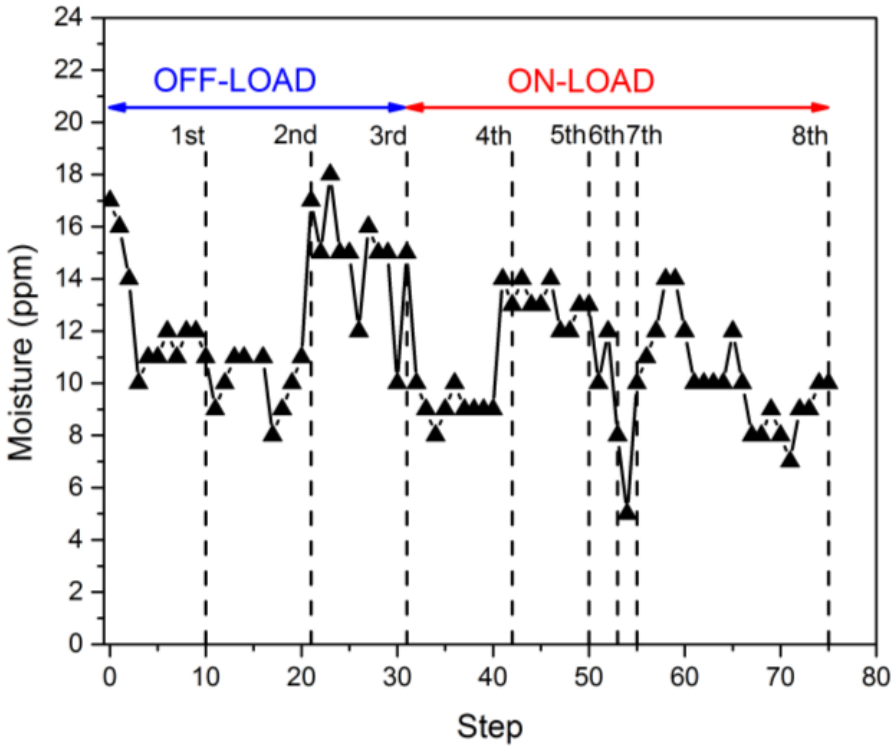


Figure 3-5 Moisture in oil profile during off-load and on-load oil regeneration of 132/33 kV transformer [7]

3.2 Preparations for the Ageing Experiment

Three groups of oil were used for the ageing experiment – new oil, service-aged oil before regeneration, and service-aged oil after being subject to regeneration. Within new oils, three different types were used, the details of which are provided in Table 3-1.

Table 3-1 Oil types used for ageing experiment

Oil Class	Oil type/label	Note
New Oil	Gemini X	New inhibited oil
	Diala S3 (S3)	New inhibited oil
	Diala S2 (S2)	New uninhibited oil
Oil before regeneration	R3	Oil taken at step 3 of on-site regeneration
Oil after regeneration	R75	Oil taken at step 75 of on-site regeneration

In this study, two oils – one from the first stage (step 3) and another from the final stage (step 75) of the previous on-site regeneration [7], were chosen to represent the oils before and after regeneration respectively. The conditions under which ageing experiments were performed are elaborated in Table 3-2.

Table 3-2 Conditions of ageing experiment

Parameter	**Values**
Oils under test	Gemini X, Diala S2, Diala S3, Non-regenerated oil, and Regenerated oil
Temperature of ageing	120 ℃
Ageing system and conditions	Sealed, Oil-paper-copper system
Oil-paper-copper ratio	70 g:7 g:17.5 cm^2
Ageing duration	9 weeks (63 days)
Sampling intervals	7, 14, 21, 28, 42 and 63 days

The ageing experiment was conducted over a period of 9 weeks (63 days). Sampling was performed regularly during this period, at 7, 14, 21, 28, 42 and 63 days. The analysis of ageing characteristics was accomplished through the measurements of TAN, LMA, HMA, and moisture for oil, and LMA, moisture, and TI for paper.

The new oil samples were processed prior to the ageing experiment, while the before and after regeneration oil samples were used directly from the impregnation stage. The steps for pre-processing were as follows:

1) Oil samples were filtered and dried in a vacuum oven at 85 ℃ for 48 hours. This step was skipped for the regenerated and non-regenerated samples in order to maintain the original features of the treated/untreated oil.
2) Paper samples (kraft paper with a thickness of 0.5 mm) were cut into uniform strips of 18 cm length and dried in an air-circulating oven at 105 ℃ for a period of 24 hours.
3) Once the oil samples and paper strips were dried, 70 g of each oil (including the regenerated and non-regenerated oils) were taken in a container, and 7 g of kraft paper was added to the system to create an oil-paper ratio of 10:1 (by weight). These samples were then further placed in the vacuum oven at 85 ℃ for a period of 24 hours in order to aid in the impregnation process.
4) Copper strips of surface area 2.94×2.94 cm (total surface area of 17.5 cm^2) were prepared and polished using sandpaper shortly before the oil-paper samples were taken out of the vacuum chamber.
5) One piece of copper strip was added to every sample. The samples were sealed with a PTFE screw cap and a gasket ring in order to reduce oxygen and moisture ingress from the atmosphere.

The initial values of the key parameters of the oil samples before ageing are given in Table 3-3. Initial TAN of oil was low for all new samples, around 0.005 mg KOH/g. Initial TAN of oil before regeneration was 0.203 mg KOH/g, while that for oil after regeneration was 0.012 mg KOH/g. There was no measurable LMA content in new oils and oil after regeneration, while LMA in oil before regeneration was 0.036 mg KOH/g. HMA content was also low for the new oils at around 0.004 mg KOH/g, while the HMA in oil after regeneration was slightly higher at 0.012 mg KOH/g. HMA in oil before regeneration was significantly higher at 0.159 mg KOH/g. The moisture in all oil samples were at similar levels (less than 3 ppm) before the start of the ageing experiment.

Table 3-3 Initial oil parameters for ageing experiment

Oil type/label	TAN (mg KOH/g)	LMA (mg KOH/g)	HMA(mg KOH/g)	Moisture (ppm)
Gemini X	0.005	0	0.003	< 3
Shell Diala S3 (S3)	0.005	0	0.004	< 3
Shell Diala S2 (S2)	0.006	0	0.003	< 3
R3	0.203	0.036	0.159	< 3
R75	0.012	0	0.012	< 3

3.3 Measurement Procedures

3.3.1 Total Acidity Number (TAN) of oil

The procedure used to measure TAN is based on automatic potentiometric measurement, according to BS EN 62021-1 [61]. The detailed procedure for measurement of TAN is illustrated in Figure 3-6 [102]. 5 g of the oil under test is dissolved in 70 ml of solvent and titrated potentiometrically against a reagent of 0.1 M Potassium Hydroxide (KOH), using a glass indicating electrode and a reference electrode (Metrohm Solvotrode 6.0229.100). The solvent used for acidity measurements is made using a combination of Toluene (50%), Isopropanol (49.5%), and water (0.5%). Batches of 1 L of this solvent were prepared, and 70 ml of the same was used for each measurement. The end point for the titration was set at a pH value of 11.5. TAN is calculated by subtracting the difference in quantity of KOH used to titrate the solvent only from the quantity of KOH used to titrate the solvent

and 5 g of the oil, multiplying the result by the molar mass and concentration of the KOH reagent, and dividing the result by the weight of the oil used (5 g).

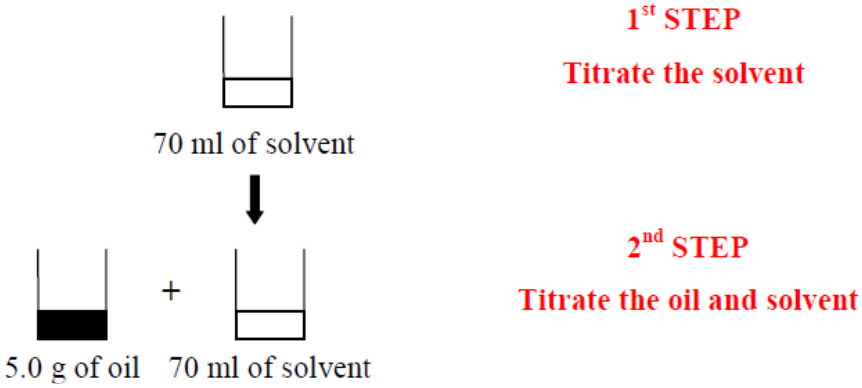


Figure 3-6 Procedure for TAN measurements [102]

TAN of oil can be calculated from Equation 3.1.

$$TAN = \frac{(v_o - v_s) \cdot m_v \cdot C_v}{w} \quad (3.1)$$

where

v_s : Volume of reagent consumed by 70 ml of solvent only

v_o : Volume of reagent consumed by 70 ml of solvent and 5 g of oil

m_v : Molar mass of reagent (g/mol) (56.1056 g for KOH)

C_v: Concentration of reagent (mol/L) (0.1 mol/L)

w : Weight of oil dissolved in solvent (g) (5 g)

3.3.2 LMA and HMA content in oil

The principle for the separation of LMA and HMA in oil is based on the chemical nature of these acids. LMA is a polar compound, which makes it soluble in other polar compounds (e.g. water). On the other hand, HMA is a less-polar compound. This would imply that by using a polar liquid extraction process, the LMA from the oil can be extracted into the polar liquid, while the HMA would remain in the oil.

In order to separate the LMA and HMA in the oil. 25 ml of the oil was mixed with an equal volume (25 ml) of distilled water and mixed overnight using a magnetic stirrer. The mixture was then allowed to be separated back into layers of oil and water. After this was accomplished, the two layers were extracted and titrated according to

BS 62021 [61]. The detailed procedure for TAN and HMA measurements in oil is illustrated in Figure 3-7 [102]. LMA and HMA in oil can be calculated according to Equation 3.1.

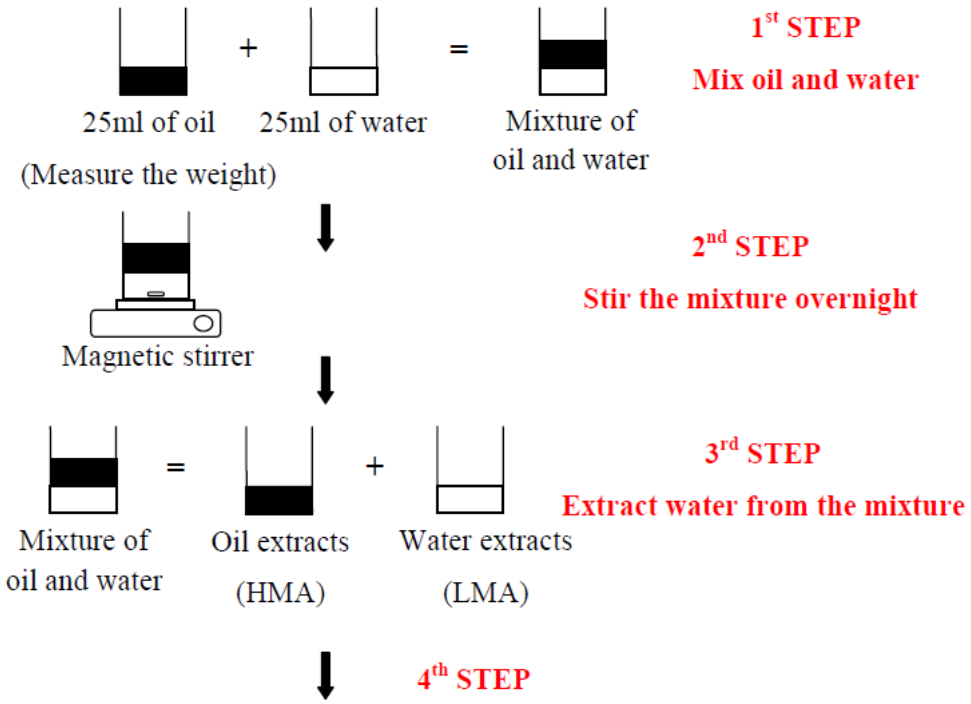


Figure 3-7 Procedure to measure LMA and HMA in oil [102]

3.3.3 Moisture in oil and paper

ASTM D1533 provides the reference for moisture measurement in oil. Moisture in oil and paper are measured by using Karl Fischer titration, which works on the principle of bipotentiometric titration (monitoring the extent of the reaction by measuring changes in electrical conductivity of the reaction solution) to measure the amount of iodine consume by water. In order to measure the moisture in oil, 2.5-3 g of oil is taken in a sealed glass vial and inserted in the Karl Fischer titrator. Moisture in paper is measured by taking a 0.025-0.030 g sample of the paper in a sealed vial after the excess oil on the surface of the paper is allowed to drip down.

3.3.4 LMA in paper

The principle of LMA extraction from paper is similar to that of LMA extraction from oil. In case of paper, a known weight of the sample, ranging from 0.5 to 1.0 g, was immersed in 25 ml of water for a period of 3 days without stirring. Following

this period, 10 ml of the water was titrated according BS 62021 [61]. The paper sample is separated and dried in a circulating oven at 70 ℃ for 2 days, and the dry weight is calculated. Finally, 40 % of this dry weight is used to calculate LMA of the paper, since only 10 ml out of the 25 ml of water was utilised for the titration. The detailed procedure to measure LMA in paper is illustrated in Figure 3-8 [102]. LMA in paper can be calculated using Equation 3.1 by substituting the weight by 40 % of the dry weight, since only 10 ml of the extract is titrated.

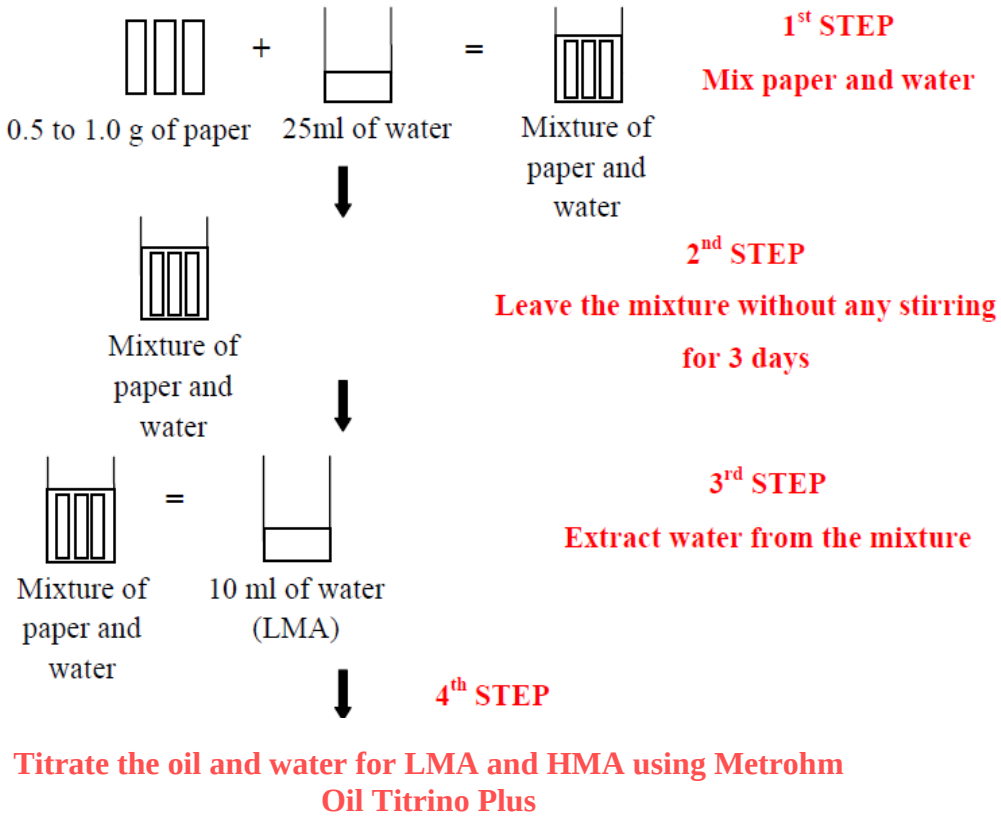


Figure 3-8 Procedure for measurement of LMA in paper [102]

3.3.5 Tensile Strength (TS) and Tensile Index (TI) of paper

Measurements of the mechanical strength of the paper were carried out based on long-span TS measurements, with a gap distance of 100 mm ± 1 mm as specified in BS 1924 [103]. An average of 10 tests of long-span TS were carried out for each sample, without the presence of any oil. Long-span TI can be calculated by dividing TS by the grammage of the paper, which in turn can be calculated by dividing the weight of the paper by its surface area. The Tensile Index has been preferred over Tensile Strength measurement since the former takes into account the grammage of the paper. The setup for measurement of long-span TS is shown in Figure 3-9 [102]. TI can be calculated as

$$TI = \frac{TS \cdot A}{w} \text{ Nm/g} \qquad (3.4)$$

where,

TS: Tensile Strength measured

A: Surface area of the paper sample (m^2)

w: weight of the paper sample (g)

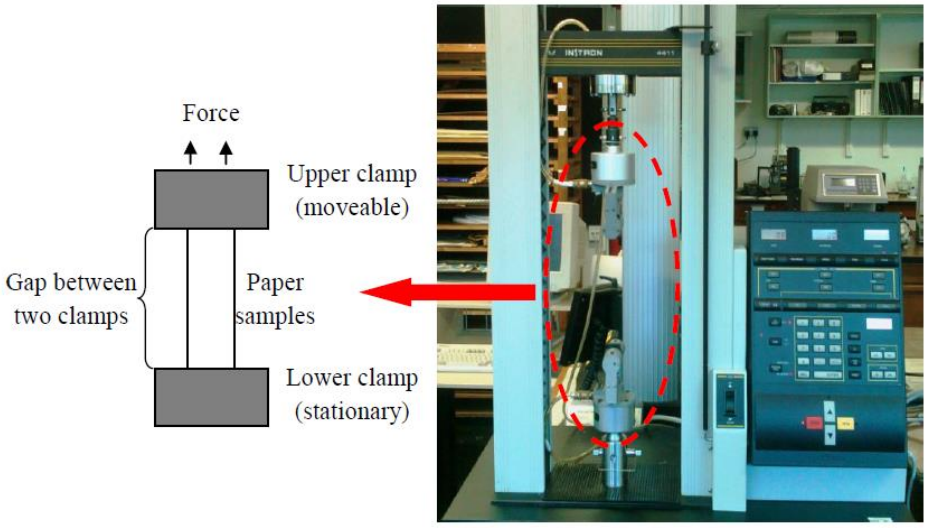


Figure 3-9 Setup for measurement of long-span TS [102]

3.4 Results and Discussions

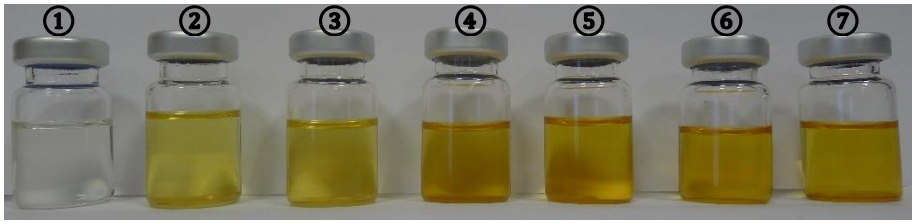
3.4.1 Ageing characteristics of oil

3.4.1.1 Colour change in oil

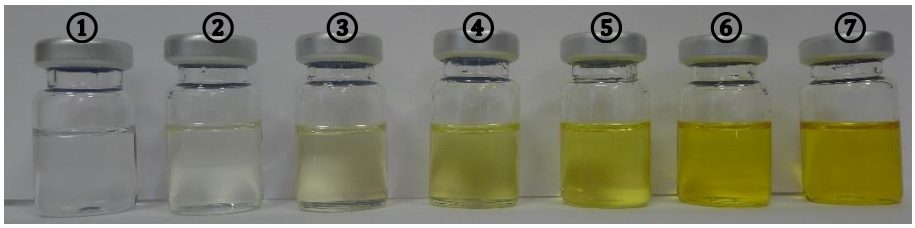
While a change in colour indicates contamination or deterioration of the oil, it is noted that colour may not necessarily be an accurate representation of the oil properties since it is dependent on the natural colour of the oil and refining methods used. Change in the colour of the oil is usually attributed to oxidation, which results in acidic products [104, 105]. Thus a lighter colour indicates a newer oil with lower acidity, while a darker colour generally indicates a higher state of ageing.

The change in colour for the various oil samples observed throughout the ageing period is presented in Figure 3-10. It is clear that the colour of the oil darkens with ageing. The colour of the uninhibited oil S2 changes at a faster rate when compared to the inhibited oils S3 and Gemini X, which change at a similar rate. The colour of oil after regeneration exhibits gradual darkening as it ages. However, its final colour

is still lighter than the initial colour of the oil before regeneration. The oil before regeneration loses clarity and changes colour to a dark brown colour at the end of the ageing experiment.



(a)



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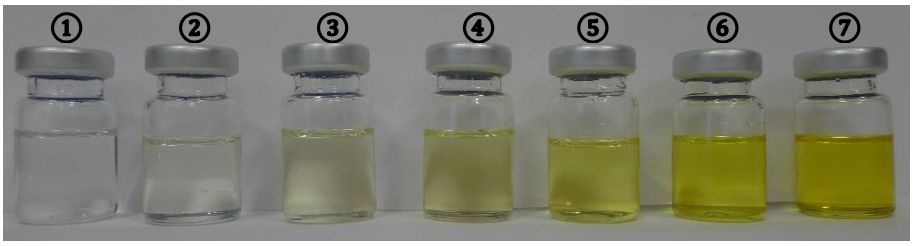

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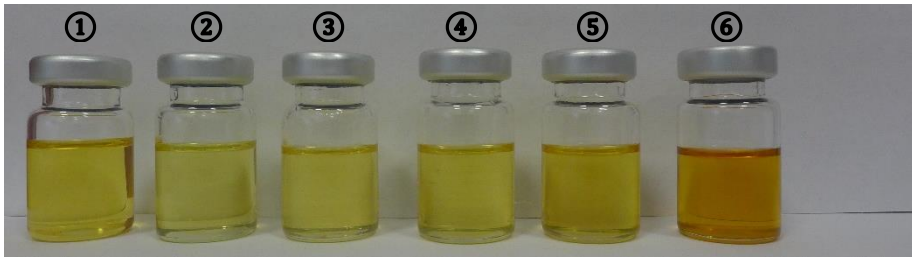

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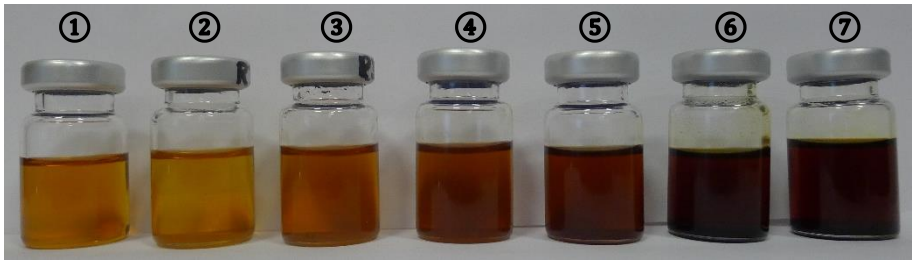


(e)

Figure 3-10 Change in colour of the oils with ageing (a) Diala S2, (b) Diala S3, (c) Gemini X, (d) oil after regeneration, and (e) oil before regeneration, at ①– 0 days, ②– 7 days, ③– 14 days, ④– 21 days, ⑤– 28 days, ⑥– 42 days, and ⑦– 63 days

3.4.1.2 Moisture in oil

Moisture in oil was observed to increase with the duration of ageing, as seen in Figure 3-11. Each result is an average of two measurements. The variation of two readings is up to 3 ppm. All samples had similar initial moisture levels of less than 3 ppm after impregnation. At the end of 63 days of ageing, the sample of oil before regeneration exhibited the highest moisture content of around 28 ppm, while the moisture in new oils were below the level of 15 ppm. The moisture in oil before regeneration was observed to exhibit a linearly increasing slope. The moisture in the oil before regeneration was notably higher than the other samples throughout the ageing period, despite the fact that its initial moisture content was comparable with the other samples. This may be due to the fact that the oil before regeneration has a high moisture saturation level, and hence an issue of partitioning of moisture. The ageing of oil after regeneration was restricted to 42 days due to limited quantity of the original sample.

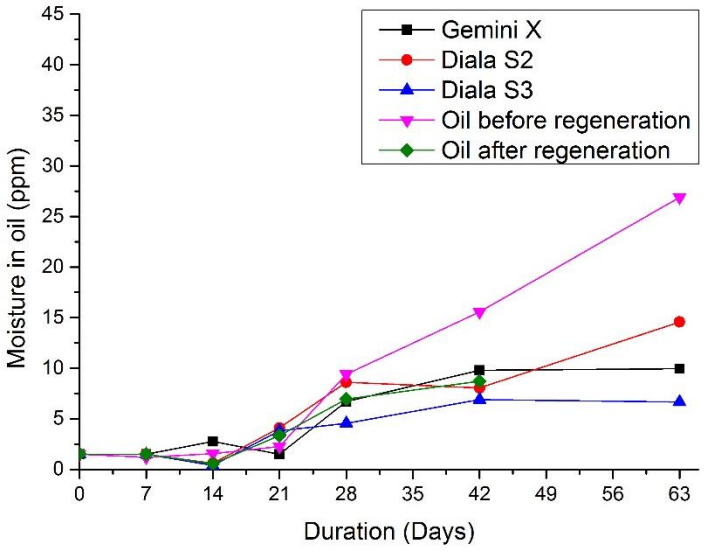


Figure 3-11 Profile of oil moisture during ageing experiment

The moisture evolution for the oil after regeneration was found to be comparable with that of other new oils. Moisture in oil after regeneration at the end of 42 days of ageing was found to be around 7 ppm, while that in the new oils was between the range of 6 and 9 ppm. Moisture in oil before regeneration at this point was 16 ppm. Higher moisture in oil in an in-service transformer would negatively affect its performance by affecting the dielectric strength of the insulation system and by promoting paper ageing.

3.4.1.3 TAN of oil

The profile of TAN for all the oils is presented in Figure 3-12. Each result is an average of two measurements. The accuracy of measurements according to the instrument manual could be up to 0.05 mg KOH/g. However, according to experience in the lab, the variation of two readings is around 0.02 mg KOH/g. It was observed that the trend for TAN of oil after regeneration is comparable to that of the new oils. The oil after regeneration reached TAN of 0.06 mg KOH/g at the end of 42 days of ageing, while the new oils attained comparable TAN levels of from 0.040 mg KOH/g to 0.065 mg KOH/g. TAN of oil before regeneration was observed to be around 0.26 mg KOH/g at the end of 42 days of ageing, which is significantly higher than the other oils. This is primarily due to higher initial acidity of 0.21 mg KOH/g. TAN for oil before regeneration increased to around 0.35 mg KOH/g at the end of 63 days of ageing, while the TAN for all the new oils stayed under 0.075 mg KOH/g.

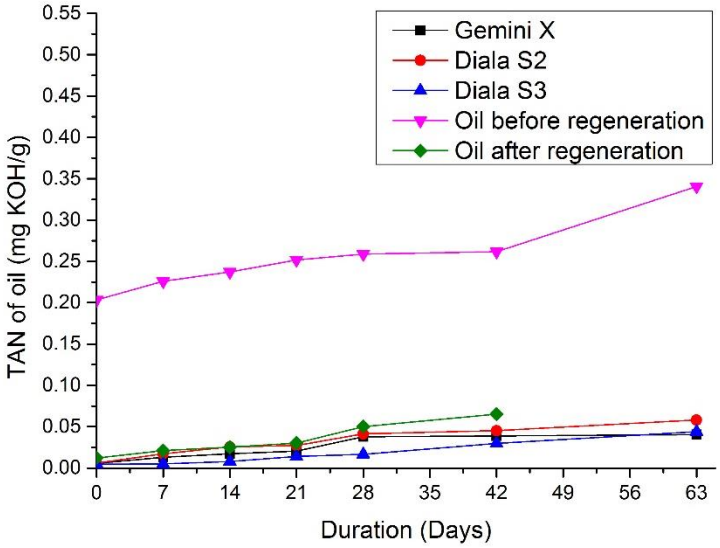


Figure 3-12 Profile of TAN of oil during ageing experiment

It can be clearly seen from Figure 3-12 that the TAN values of oil before regeneration are much higher, and increase at a faster rate when compared to the other oils, suggesting that regenerated oil performs better than non-regenerated oil. The increasing trend of TAN in oil before regeneration is higher than that of other oils, but not as fast as expected. Oxidation of oils is accelerated by the presence of acids and catalysed by the presence of copper ions [106]. Thus, it is natural to assume that oil with a higher initial acidic content, such as the oil before regeneration, would exhibit a slightly higher rate of ageing when compared to the newer oils.

It is noted that the values of TAN at the end of this study conform to the range of the values reported by Liao et al. under similar conditions [23]. In correlating the colour of the oil (Figure 3-10) with the acidity level, it is observed that oils exhibiting similar colours visually (e.g. oil after regeneration at 42 days of ageing and oil before regeneration at 0 and 7 days of ageing) show large differences in the TAN values – oil before regeneration exhibits an initial TAN of more than 0.2 mg KOH/g, while oil after regeneration exhibits a TAN of about 0.275 mg KOH/g at the end of 42 days of ageing. This clearly indicates absence of a correlation between observed colour of the oil and the state of ageing.

3.4.1.4 LMA and HMA in oil

The profile of LMA in oil with ageing duration is shown in Figure 3-13. Each result is an average of two measurements. While the variation due to titration can be assumed to be same as that of TAN (around 0.02 mg KOH/g), there could be larger errors introduced due to the LMA/HMA separation process. This also holds true for HMA results in Figure 3-14. It is noted that the separation process is to be improved. LMA in oil was observed to follow the trend of TAN of oil. The LMA in oil before regeneration was the highest in terms of absolute value and rate of increase. It is to be noted that the initial LMA of the oil before regeneration was about 0.037 mg KOH/g, which was significantly higher than the other oils. Initial LMA in new oils was observed to be minimal, since it is premised that LMA is mainly generated by paper ageing [31, 32].

LMA in oil did not significantly increase in the new oil and the sample of oil after regeneration during the initial periods of ageing, particularly up to 21 days. During this period, LMA in oil before regeneration increased to around 0.08 mg KOH/g, reaching a value of 0.11 mg KOH/g by the end of 42 days of ageing, in comparison to 0.04 mg KOH/g for the oil after regeneration. The LMA in new oils stayed below 0.02 mg KOH/g.

The lower LMA content in oil after regeneration throughout the ageing period suggests that the ageing rate of paper in such oils is slower, particularly when compared to the rate of increase of LMA in oil before regeneration during this period, signifying faster ageing of paper. Further evidence for this can be obtained from the

values of LMA in paper (Figure 3-17), which confirms higher values of LMA generated in the case of paper aged in oil before regeneration.

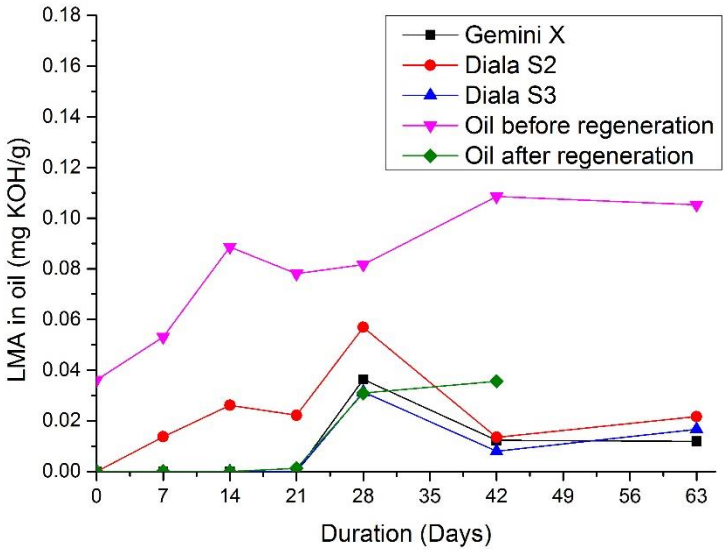


Figure 3-13 Profile of LMA in oil during ageing experiment

Ingebrigsten et al. [34] proposed that LMA tends to be absorbed by the paper. The authors further suggested that the combined effect of water and LMA influences the ageing of the oil-paper system.

While the LMA indicates paper ageing, evolution of HMA could be considered to be more indicative of the oil ageing [102]. The profile of HMA in oil against ageing duration is illustrated in Figure 3-14. It was observed that the oil before regeneration had a significantly higher initial HMA content owing to higher TAN in comparison with the oil after regeneration and new oils.

At the end of 42 days of ageing, the HMA in oil before regeneration increased to around 0.19 mg KOH/g, while that for oil after regeneration stayed below 0.05 mg KOH/g. HMA content in new oils stayed in similar levels of under 0.07 mg KOH/g. The HMA content in oil before regeneration stayed in the range of 0.19 mg KOH/g between the period of 42 and 63 days. However, it is possible that this profile without clear increasing trend is due to errors caused by the HMA/LMA separation process.

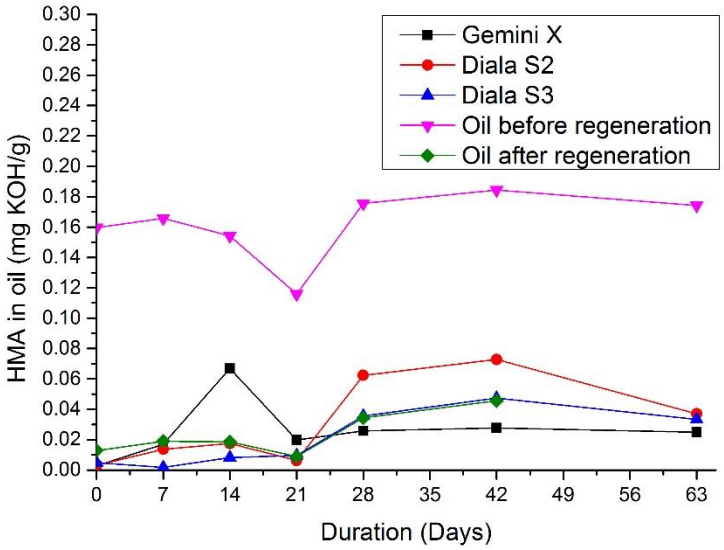


Figure 3-14 Profile of HMA in oil during ageing experiment

There was no clear relationship found between the ratio of LMA, HMA and TAN of oil over the ageing period. A comparison of LMA, HMA and TAN for oil after regeneration is presented in Figure 3-15. It was observed that the sum of the measured LMA and HMA content in oil did not necessarily equal to the TAN of the oil. This is due to the fact that the LMA and HMA separation process relies upon the extraction of polar LMA from oil using water, a polar solvent. As mentioned earlier, this process has not been fully developed and could introduce uncertainties in measurement. It is also noted that the quantities measured in this test are very low in terms of absolute value, and thus could be more sensitive to measurement errors.

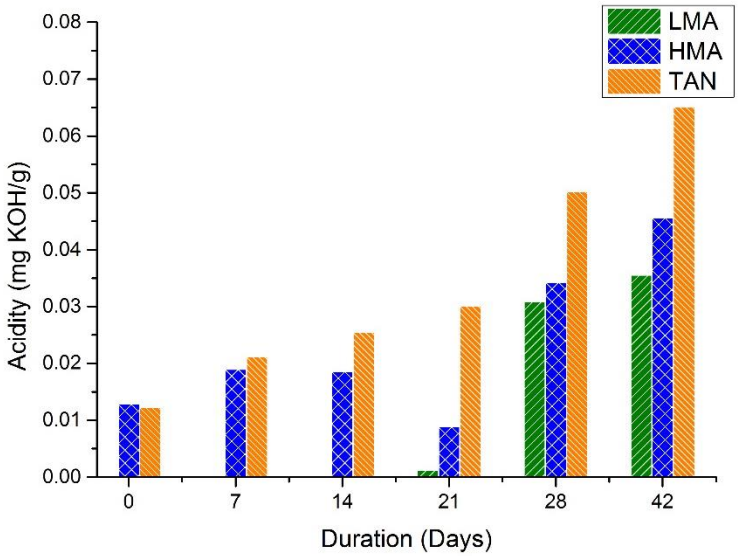


Figure 3-15 Comparison of LMA, HMA and TAN for oil after regeneration

The LMA and HMA as a percentage of total acidity (LMA+HMA) for the oil before regeneration is presented in Table 3-4. It is observed that the ratio of LMA to HMA

in the oil before regeneration during the 63 day ageing period is approximately 30%:70%. However, this ratio was not consistent in the other oil samples. It is further noted that the LMA in oil for most of the new oils and oil after regeneration was near zero during the first few weeks, and hence calculating LMA and HMA ratio may not be representative.

Table 3-4 Ratio of LMA and HMA in oil before regeneration

Ageing duration (days)	LMA (%)	HMA (%)
0	18.5	81.5
7	24.2	75.8
14	36.5	63.5
21	40.3	59.7
28	31.7	68.3
42	37.0	63.0
63	37.7	62.3
Average	**32.3**	**67.7**

3.4.2 Effect of oil condition on paper ageing

3.4.2.1 Moisture in paper

Figure 3-16 shows the profile for moisture concentration in paper during the ageing experiment. It is noted that moisture levels stayed under 1% for the duration of the experiment for all samples except the oil before regeneration, where the paper moisture increased up to approximately 1.5%.

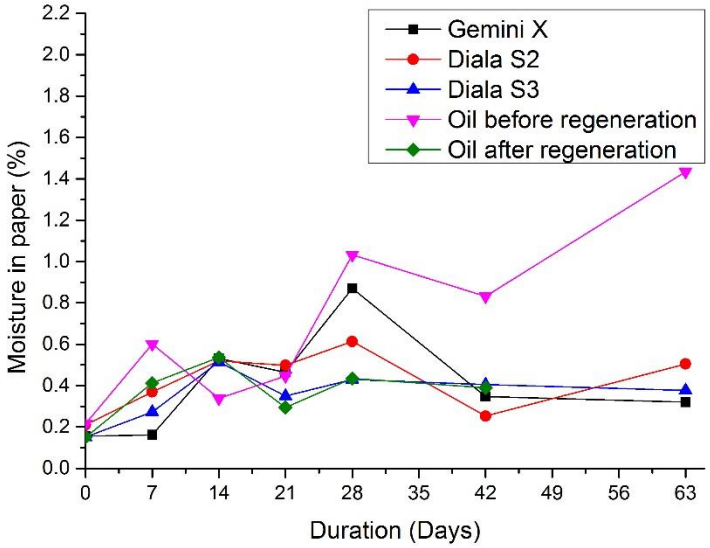


Figure 3-16 Profile of paper moisture during ageing experiment

In Figure 3-16, each point is an average of two measurements. It is noted that the variation of two measurements is around 0.05%.

Similar to the oil moisture it is observed that the moisture in paper aged in oil before regeneration increases at a higher rate, and to considerably higher values, when compared to the other oils. It is further noted that the performance of paper aged in oil after regeneration is comparable with that of new inhibited and uninhibited oils.

The values of moisture in paper obtained in this study conform to values of moisture in paper reported in the ageing experiments conducted by Liao et al. [107]. Utilising a sealed new mineral oil-paper-copper system at 110 ℃, the investigators reported that the moisture in paper was approximately 1.2% at the end of 63 days of ageing, beyond which the moisture in paper started reducing due to a shift in the equilibrium owing to the aged state of the paper. Similar results of paper attaining around 1% moisture levels at the end of the ageing process were also reported by Saha et al. [108].

3.4.2.2 LMA in paper

Measurements of LMA content in paper were carried out to assess the chemical degradation of the paper with ageing. The trend for LMA evolution in paper is shown in Figure 3-17. LMA in paper was at similar levels for all samples at the start of the ageing experiment given the new condition of the paper. However, it is noted that for the paper sample in oil before regeneration, the LMA in paper increased to a slightly higher value of around 0.09 mg KOH/g after the impregnation process. This could be attributed to the higher initial LMA in the oil, as seen from Figure 3-13. Given the initial LMA in the oil before regeneration was around 0.04 mg KOH/g, and the oil-paper ratio was 10:1, it is conceivable that the LMA migrated from the bulk of the oil into the paper, causing an increase in the initial LMA content of the paper post-impregnation. This also provides evidence to support that LMA in the system tends to be attracted towards the paper.

At the end of 42 days of ageing, LMA content in paper aged in oil before regeneration was at significantly higher levels of 3.5 mg KOH/g in comparison with the paper aged in new oils and oil after regeneration. LMA in paper aged in oil after regeneration measured at around 2 mg KOH/g, similar to those of papers aged in the new oils. This provides evidence to support the premise that rate of ageing of the paper is slower after oil regeneration. The trends for LMA in paper for all samples were observed to be linearly increasing, finally reaching a value of approximately

5 mg KOH/g for oil before regeneration at the end of 63 days, while that for the new oils stayed in levels below 3 mg KOH/g.

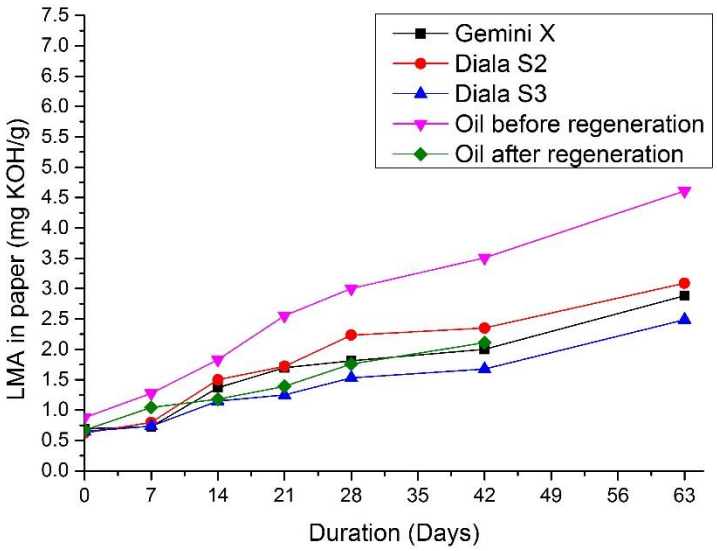


Figure 3-17 Profile of LMA in paper during ageing experiment

Similar to LMA and HMA in oil, the extraction of LMA from paper is yet to be standardised. Each point in Figure 3-17 is an average of two readings. The LMA content in paper is considered to represent the chemical by-products of the paper through the ageing process. Higher LMA would also link to higher levels of moisture, as both moisture and LMA are a by-product of hydrolysis and the ageing process. From the results in Figure 3-17, it could be inferred that new paper performs well in regenerated oil, and poorer in non-regenerated oil. It is further noted that the levels of LMA in paper attained in this study conform to those published by Liao et al. [107] under similar ageing conditions. The investigators reported a linear relationship between the LMA content in paper and the ageing duration, with LMA in paper reaching values of up to 6 mg KOH/g at the end of around 60 days of ageing in a mineral oil-paper-copper system at 100 ℃. It is noted that the same extraction procedure for LMA in paper, as the one used in this study, was employed by the investigators, which was originally proposed by Lundgaard et al. [31, 60].

Lundgaard and Igebrigsten [31, 60] also investigated the detrimental effects of acids, and the significance of molecular weight on the ageing of cellulose in an oil-paper system. They attributed the greater effect of LMA on the ageing of paper to hydrolysis by the catalytic influence of the H^+ ions, originating from the dissociation of carboxylic acids in water. The LMA tends to be easily absorbed by the cellulose

fibres due to their lower weight and high polarity, which is governed by the dissociation number (pKa value) of the acids. Judging by the results obtained from this investigation, the higher values of initial LMA in the sample of oil before regeneration would lead to an accelerated degradation of the paper, which would in turn lead to an increased moisture content and LMA in the system. This self-accelerated reaction would mean that the paper samples aged in the oil before regeneration would reduce in mechanical strength at a faster rate in comparison with paper aged in newer oil samples, where the initial LMA content in the system is low.

3.4.2.3 Tensile Index of paper

The mechanical strength of the paper reduces with ageing. The trend for the reduction of Tensile Index (TI) of the paper samples with age is shown in Figure 3-18. It is observed that the TI of paper aged in oil before regeneration reduces at a faster rate until 42 days, when compared to the other oils. Initial TI for all the samples were 105 Nm/g, which is the value for new paper. This value reduced to below 65 Nm/g at the end of 42 days for the paper aged in oil before regeneration, while it was approximately 80 Nm/g for the paper aged in oil after regeneration. The TI for papers aged in new oils were around 75 Nm/g at the end of 42 days of ageing, and reduced to the range of 60-70 Nm/g at the end of 63 days of ageing. TI for paper aged in oil before regeneration reduced to a value of 58 Nm/g at the end of 63 days of ageing, and was the lowest among all the other paper samples. The analysis of the TI of the paper samples supports that the ageing performance of oil and paper insulation is improved after oil regeneration, as is visible from the overall trend for TI of oil before and after regeneration. Furthermore, these results indicate that the performance of paper aged in regenerated oil is comparable with that of new oils.

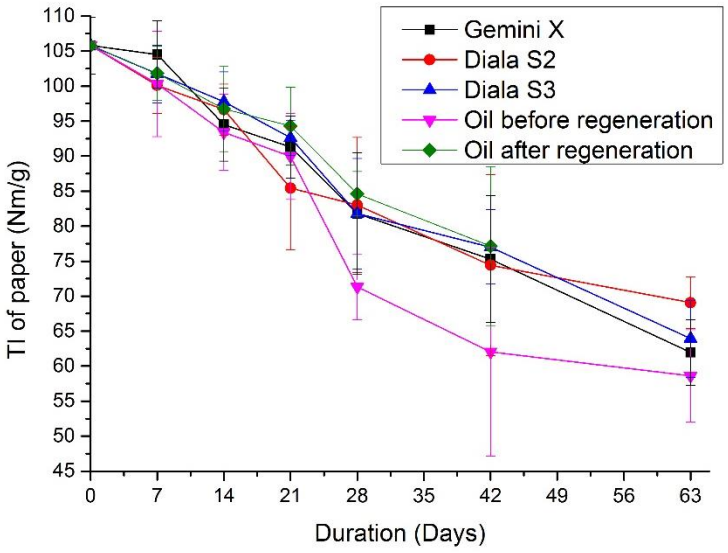


Figure 3-18 Profile of Tensile Index (TI) of paper during ageing experiment

TI of paper aged in oil before regeneration is seen to drop to comparatively lower values, particularly visible in the samples at 28 and 42 days. Laundgaard et al [15, 32], suggested that a correlation between the LMA, water and rate of ageing of paper exists, and the initial faster reduction of TI is due to faster ageing of the amorphous regions of the cellulose fibres, and the later slower rate of reduction due to slower degradation of the crystalline regions. Several studies also provided evidence to suggest that higher acid content in the paper would accelerate the ageing process, catalysed by the dissociation of the carboxylic acids [31-33, 60, 107]. Presence of moisture enhances this dissociation, thus having a multiplicative effect when combined with the acids [32].

Considering the LMA in paper and the reduction in mechanical strength of the paper, the TI profile of the paper samples are in agreement with the previous inference of the accelerated ageing in the oil before regeneration due to a greater initial LMA content. Furthermore, a clear reduction in the rate of ageing is visible in the case of the paper aged in oil after regeneration, which is in agreement with the trend observed by Lundgaard et al. [31].

Azis et al. [109] proposed a relationship between the LMA in paper and the TI, furnishing evidence from scrapped transformers to suggest that LMA increased with a reduction of TI. While it is suggested that this relationship is obscure when the LMA content is below 2.5 mg KOH/g (under which range a majority of our samples lie), a graphical representation of this relationship from was provided. It is noted that

the majority of the values of TI correspond to the range of expected LMA content in paper (or vice-versa) in accordance with the relationship proposed by the investigators.

3.5 Summary

It is found that the performance of the regenerated oil is better than that of the non-regenerated oil, and is comparable to that of new oils. In terms of the impact of oil regeneration on paper ageing, the TI of paper aged in oil after regeneration reduces at a rate similar to that of paper aged in new oils, and at a considerably slower rate in comparison with non-regenerated oil. These results conform to previous findings that the oil condition plays a role in determining the ageing rate of paper, and therefore support the theory that oil regeneration could slow down the paper degradation in the transformer by removing acid and moisture from the insulation system.

Chapter 4. Effect of Oil Regeneration on Paper Conditions

4.1 Introduction

Oil regeneration is a transformer insulation reconditioning technique which can be performed both off-line and on-line. However, there is a lack of evidence showing the effect of this process on conditions of the paper insulation, which in turn affects the life of a transformer. This chapter focusses on oil regeneration experiment on a 77-year-old retired distribution transformer. Electrical testing and post-mortem analysis of the transformer were conducted, aimed at investigating the design aspects and collecting information on the insulation conditions prior to the oil regeneration. Temperature and moisture sensors were installed to monitor the conditions within the transformer during the oil regeneration. Oil regeneration was then performed on the transformer in two stages, with regular oil sampling to analyse the changes in key oil parameters, namely TAN and moisture. This was accompanied by paper sampling at the end of each stage in order to study the effects of oil regeneration on paper conditions, particularly moisture and LMA content.

The transformer under test is a 77-year-old 6.4/0.4 kV Distribution Transformer (DT), which was retired from an Electricity North West substation in 2013, the details of which are presented in Table 4-1. Oil samples were collected before retirement, and a range of physical and chemical parameters were analysed, which are presented in Table 4-2 [110]. It was observed that the oil was highly aged with an acidity of 0.89 mg KOH/g, and a moisture content of 42 ppm. The oil was reported to be dark and cloudy, with an AC breakdown voltage of 34 kV for a 2.5 mm gap.

Table 4-1 Details of the transformer under test

Manufacturer	Metropolitan Vickers (MetVicks)
Year of manufacture/retirement	1936/2013
Rating (KVA)	750
HV/LV (V)	6400/405
HV Current rating (A)	88.2
LV Current rating (A)	1880
Configuration (HV/LV)	Δ -Y
Total Oil Volume	1273 L (280 Gallons)
Weight of Core and Winding	2360 Kg (5200 Lbs.)
Total weight including Oil	4600 Kg (10150 Lbs.)

Table 4-2 Oil properties of the transformer under test measured before retirement [110]

Property	**Unit**	**Standard**	**Value**
Colour		BS EN ISO 2049	5.9
Colour (Visual)			Black
Appearance		IEC 296	Cloudy
Sediment			Oil/water Emulsion
Smell			Burnt
Acidity	mg KOH/g		0.89
Water content	mg/kg	BS EN ISO 60814	42
Total PCBs	mg/kg	BS EN ISO 61619	0.9
2 FAL	mg/kg	BS EN ISO 61198	0.04
Electrical Strength	kV	BS EN ISO 60156	34.0
Fibre	F1-F6		F5
Hydrogen H2	µl/l	BS EN IEC 60567	22.0
Oxygen O2	µl/l	BS EN IEC 60567	20349.0
Nitrogen N2	µl/l	BS EN IEC 60567	74525.0
Carbon Monoxide CO	µl/l	BS EN IEC 60567	127.0
Methane CH4	µl/l	BS EN IEC 60567	5.0
Carbon Dioxide CO2	µl/l	BS EN IEC 60567	1071.0
Ethylene C2H4	µl/l	BS EN IEC 60567	1.0
Ethane C2H6	µl/l	BS EN IEC 60567	0.0
Acetylene C2H2	µl/l	BS EN IEC 60567	0.0
Total Gas Measured	µl/l	BS EN IEC 60567	10.0
Total Gas Calculated	ml/100 grams		96100.0
Combustible Gas Content Calculated	ml/100 grams		1226.0

A flow chart for the design of the oil regeneration experiment is presented in Figure 4-1. The study consisted of multiple key stages – electrical testing, post-mortem inspection, sensor installation, and the oil regeneration experiment. The oil regeneration experiment was conducted in two stages – stage 1 aimed to 'clean' the

oil, and stage 2 aimed to 'clean' the paper. Sampling of paper was conducted at three instances, namely before oil regeneration (before stage 1), after stage 1 (in between stage 1 and stage 2), and after stage 2. Oil samples were collected regularly during the entire process.

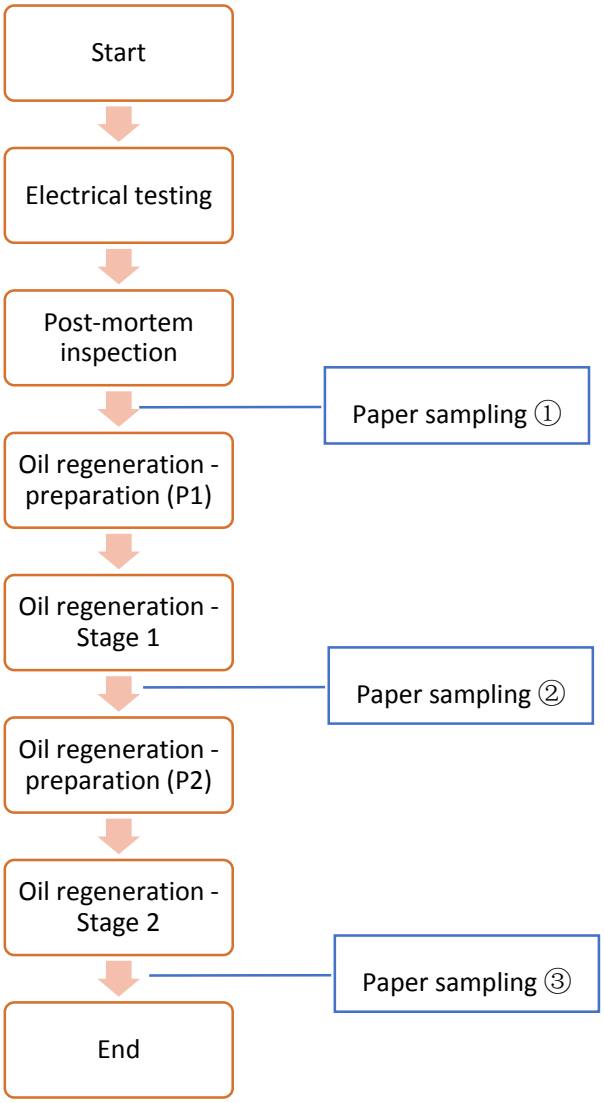


Figure 4-1 Oil regeneration experiment flow chart

4.2 Electrical Testing of the Transformer

The transformer under test was retired following a scheduled arrangement rather than a failure in service. Since it had served for a long period and displayed severe ageing symptoms, it is interesting to investigate the electrical performance of the transformer under such an aged condition. As part of the investigation, Lightning Impulse (LI) test and AC voltage withstand tests were performed on the transformer.

4.2.1 Short-Duration AC voltage withstand test (ACSD)

Although IEC 60076-3 specifies a voltage of 20 kV be applied for transformers of this rating, it was decided to not exceed the rated voltage (6.4 kV). The test setup used for the AC voltage withstand test is shown in Figure 4-2.

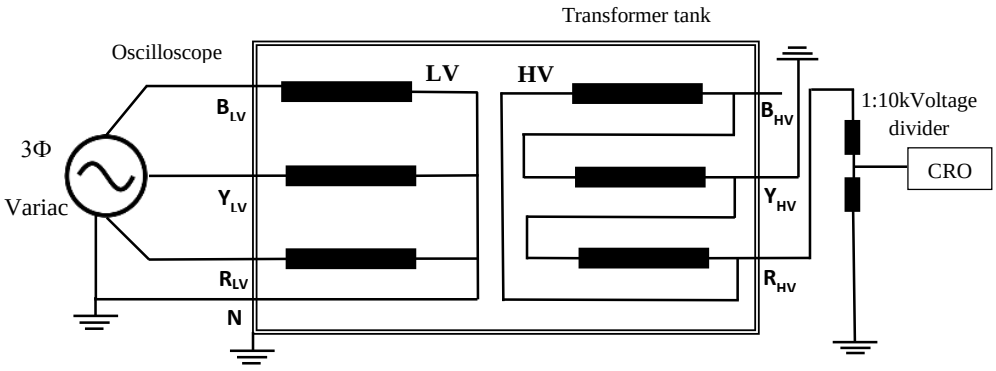


Figure 4-2 Test circuit for ACSD on 6.4/0.4 kV DT

A 3-phase variac was used to apply AC voltage to the low voltage (LV) side of the transformer following the profile shown in Figure 4-3. A voltage divider was used to measure the induced voltage on the high voltage side with one phase terminal as the measuring port and another earthed. This test was rotated to cover all three arms of the HV delta connection, as shown in Table 4-3.

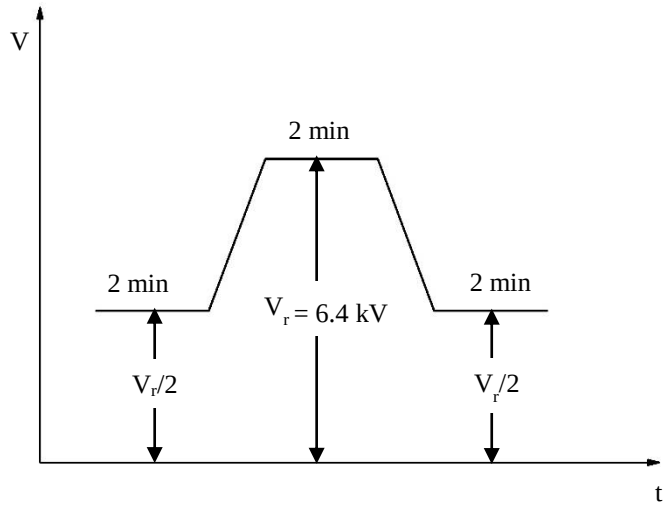


Figure 4-3 Applied voltage profile for ACSD test on 6.4/0.4 kV DT

Table 4-3 Terminal rotation sequence for ACSD test on 6.4/0.4 kV DT

Measured terminal	Earthed terminal
R_{HV}	Y_{HV}
Y_{HV}	B_{HV}
B_{HV}	R_{HV}
B_{HV}	Y_{HV}

The results of the ACSD test are presented in Table 4-4. There was no breakdown/flashover observed during the entire duration of the test, and the transformer was deemed to pass the test.

Table 4-4 ACSD test results for 6.4/0.4 kV DT

Configuration	AC withstand Test result
R_{HV} - Y_{HV}	**Pass**
Y_{HV} - B_{HV}	**Pass**
B_{HV} - R_{HV}	**Pass**
B_{HV} - Y_{HV}	**Pass**

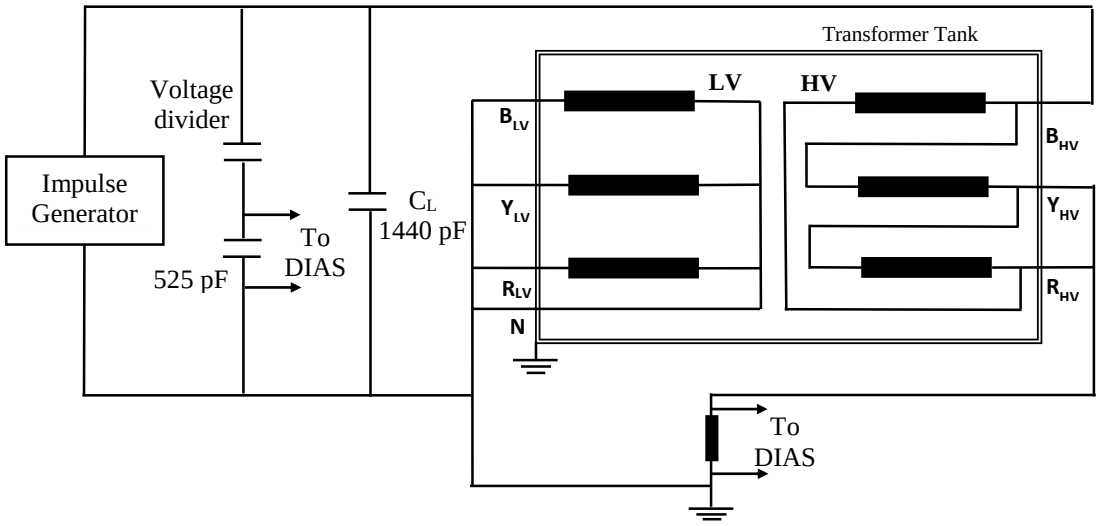
PD measurements were also attempted during the ACSD. However, these were unsuccessful due to several challenges faced during the PD test, including lack of physical connection points on the transformer which called for improvised termination of the cables, a low oil level inside the transformer which left the conductors exposed to the atmosphere, and a high system noise. These attempted PD measurements are presented in Appendix A.

4.2.2 Lightning Impulse (LI) test

The purpose of the lightning impulse test is to ensure that the transformer insulation can withstand any lightning overvoltage which may occur during service. Impulse test levels have been standardized in IEC 60076-3. LI test is a type test for transformers of this rating. Specifications for the LI test waveform is made through the duration of the wave front (called the rise time) and the duration taken to reach 50% value of the tail (called the tail time). The standard duration of a LI waveform is 1.2 µs/50 µs with allowed tolerance values of ±30% and ±20% on the rise and tail times respectively. The applied voltage waveform is recorded, along with the current waveform flowing from the tested winding to the earth for fault analysis. The test sequence consists of an impulse at a reduced voltage followed by three subsequent impulses at the rated testing voltage. This is then followed by another impulse at the same reduced voltage as previously applied. Absence of significant differences between the voltage and current transients recorded at the reduced voltages and those

recorded at full rated test voltages indicates that the winding has withstood the test. Any difference in the current waveforms could be an indication of failure.

According to IEC 60076-3, the full test voltage for this transformer's rating is 40 kV. The test sequence was chosen as one standard negative impulse at a reduced voltage of 25 kV followed by three successive impulses at full test voltage of 40 kV, followed by a final impulse at the same reduced voltage of 25 kV. The test setup is presented in Figure 4-4. A HAEFELY made impulse generator capable of generating impulses of up to 2000 kV, set at a single stage, was used to provide the test voltages. In order to adhere to the standard waveshape, a 1440 pF load capacitance was connected in parallel to the test transformer. A measuring impedance of 0.2 Ω was used for current readings. A capacitive voltage divider was used to measure the applied impulse voltage. The current and voltage signals were analysed using the Digital Impulse Analysing System (DIAS).



DIAS: Digital Impulse Analysing System

Figure 4-4 Test setup for Lightning Impulse (LI) test on 6.4/0.4 kV DT

It was observed that the impedance of the windings was very low and hence obtaining the standard impulse waveform was difficult. However, overshoot was restricted under ±5%. The time interval between two successive impulses was maintained at a minimum of 3 minutes. At the end of each test sequence, the current waveforms before and after application of the full test voltages were compared. The test scheme is presented in Figure 4-5. All three phase terminals of the HV side of the transformer were tested.

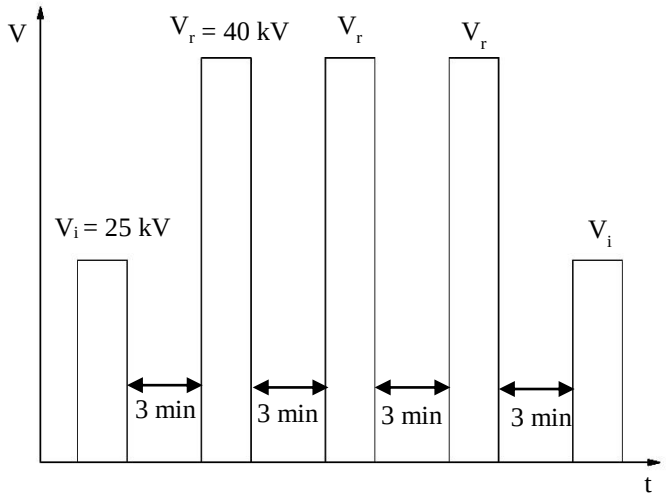


Figure 4-5 Impulse voltage application scheme for Lightning Impulse (LI) test on 6.4/0.4 kV DT

Examples of applied impulse voltage waveforms and current waveforms are shown in Figure 4-6 and Figure 4-7 respectively. In order to analyse the result of the impulse test, the current waveforms before and after the application of the three rated voltage impulses were compared, an example of which is presented in Figure 4-8

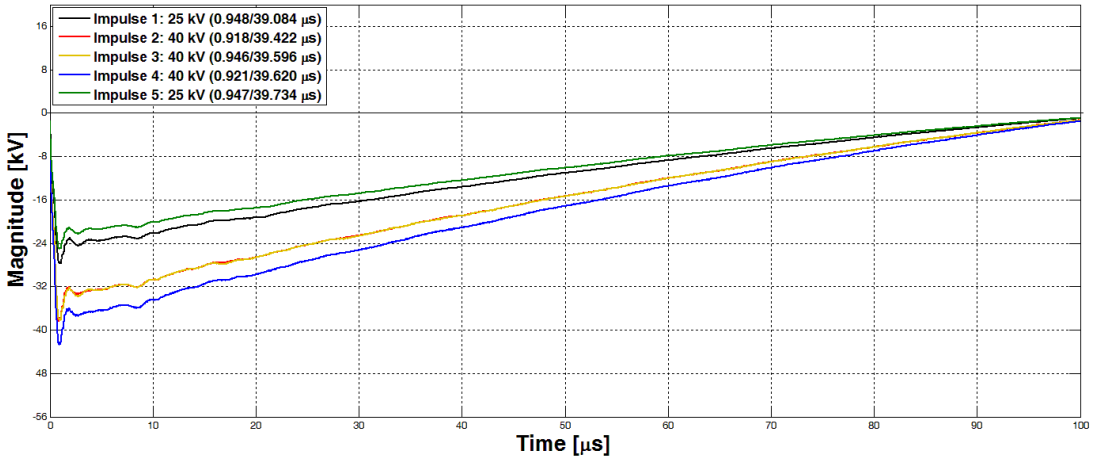


Figure 4-6 Impulse voltage waveforms recorded during LI tests on B phase of 6.4/0.4 kV DT

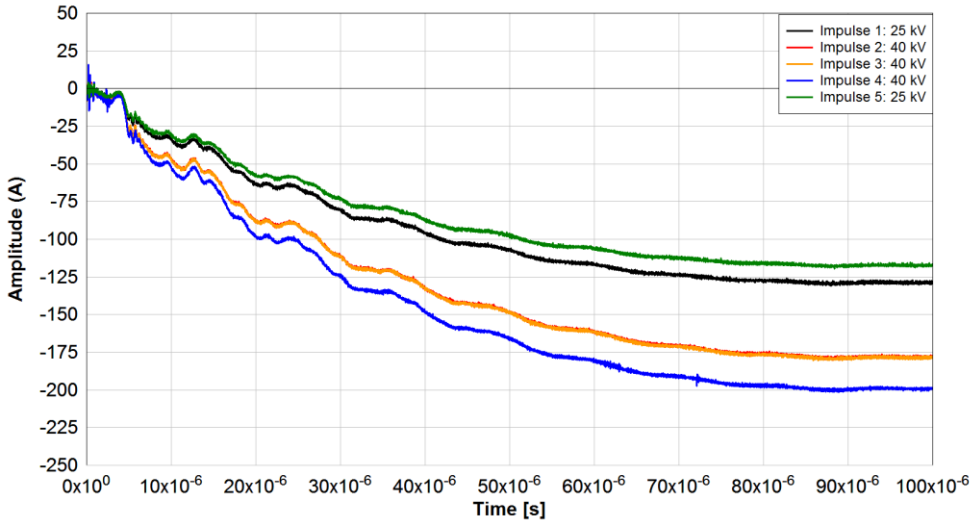


Figure 4-7 Current waveforms recorded during LI test on B phase of 6.4/0.4 kV DT

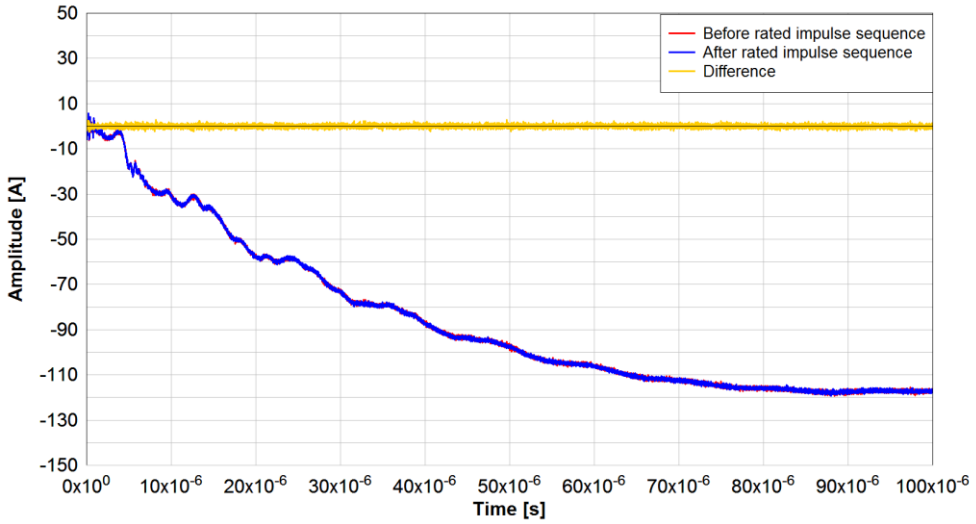


Figure 4-8 Comparison of current waveforms of B phase of 6.4/0.4 kV DT before and after application of rated voltages

The results of the impulse test are elaborated in Table 4-5. There was no noticeable breakdown observable from the voltage waveforms during all 40 kV impulse tests on all three phases. There was no remarkable difference in the current waveforms between before and after application of the 40 kV impulses for the Y_{HV} and the B_{HV} phase tests. An inspection of the current waveforms revealed a transient peak during the first two full-voltage impulse applications on Y_{HV}. It is noted that during application of the third 40kV impulse application, this transient peak had completely vanished.

Table 4-5 Result of LI test on all phases for 6.4/0.4 kV DT

Phase under test	**Impulse number**	**Impulse Level (kV)**	**T_r/T_t (µS/µs)**	**Observation/Result**
R_{HV}/ B_{HV}	1	31.181	0.967/40.434	No fault/breakdown
	2	37.715	0.967/41.052	No fault/breakdown
	3	46.671	0.918/40.092	No fault/breakdown
	4	42.489	0.966/40.924	No fault/breakdown
	5	25.011	0.963/40.790	No fault/breakdown
Y_{HV}/ R_{HV}	1	25.968	0.964/38.566	No fault/breakdown
	2	46.735	0.930/39.090	No fault/breakdown; high transient peak in current waveform near 2 µs
	3	46.709	0.928/38.603	No fault/breakdown; attenuated peak in current waveform shifted to near 12 µs
	4	40.340	0.935/39.253	No fault/breakdown; transient peak disappeared from current waveform
	5	26.628	0.963/38.742	No fault/breakdown
B_{HV}/ Y_{HV}	1	27.609	0.948/39.084	No fault/breakdown
	2	38.024	0.918/39.422	No fault/breakdown
	3	38.037	0.946/39.596	No fault/breakdown
	4	42.476	0.921/39.620	No fault/breakdown
	5	24.923	0.947/39.734	No fault/breakdown

4.3 Post-mortem Analysis of the Transformer

Prior to conducting the oil regeneration experiment, oil samples were collected from the oil tap at the bottom of the transformer tank. While the values shown in Table 4-2 were obtained from the oil sampled before the transformer was retired, certain properties were observed to have changed during the analysis of the oil samples collected before the post-mortem inspection, as shown in Table 4-6. Moisture in the oil was found to be at approximately 18 ppm on an average, measured from multiple samples collected from the top and bottom of the transformer tank. This reduction in moisture could be caused by the equilibration of moisture at room temperature, which would result in a higher moisture migration into the cellulose. The higher moisture content measured when the transformer was in-service could be due to the sampling at a higher operating temperature of the oil. It is noted that there was no visible free water during the first laboratory sampling from the oil tap located at the bottom of the transformer tank.

Table 4-6 Oil properties measured before post-mortem inspection at the University of Manchester laboratory

Parameter	**Location**	**Values**			**Average**
		Sample 1	**Sample 2**	**Sample 3**	
Moisture in oil (ppm)	Top	17	18.5	23.75	18.4
	Bottom	19.15	14.25	17.45	
TAN of oil (mg KOH/g)	Top	0.77	0.77	0.71	0.74
	Bottom	0.74	0.74	0.72	

The transformer was then de-tanked in order to carry out a post-mortem analysis. This activity served several purposes, including:

1) Providing insight into the physical structure of transformers designed nearly eight decades ago,
2) Investigating the winding and core design and conditions, which could indicate a history of failure/destructive activity,
3) Permitting the sampling of winding insulation from a targeted phase, in order to analyse the ageing condition of the paper, and
4) Facilitating the installation of temperature and moisture sensors and pre-conditioned paper samples.

Once the core assembly was succesfully detanked, visual inspection was conducted. Design aspects including the winding configuration, disc count, component dimensions, presence and location of tap changers were documented. Further, indications of ageing in the form of sludge deposists, damaged paper on windings, signs of arcing and tracking were also noted.

The transformer was observed to be designed with a disc-type winding. The HV winding contained 64 discs, each of which had 4 turns. A top-view inspection of the LV side revealed that each LV disc contains 3 turns. The windings displayed a colour profile in the outermost layer of the HV windings, with the bottom discs exhibiting a significantly darker colour in comparison with the top discs, as shown in Figure 4-9. Closer observation revealed particle and sludge deposits on these bottom discs. Five tappings were observed on each phase near the centre of the HV winding. A central band of two discs in the tapped area of the HV winding were observed to be darker than its surrounding discs. The leads connecting to the tap changer were wrapped by crepe paper.

No obvious tracking and treeing signs were observed on the winding insulation. However, severe damage to the connecting cables were noticed, where the insulation was burnt and melted. The front view of the core assembly is presented in Figure 4-9, and the physical dimensions of the transformer structure are shown in Figure 4-10 and Figure 4-11.

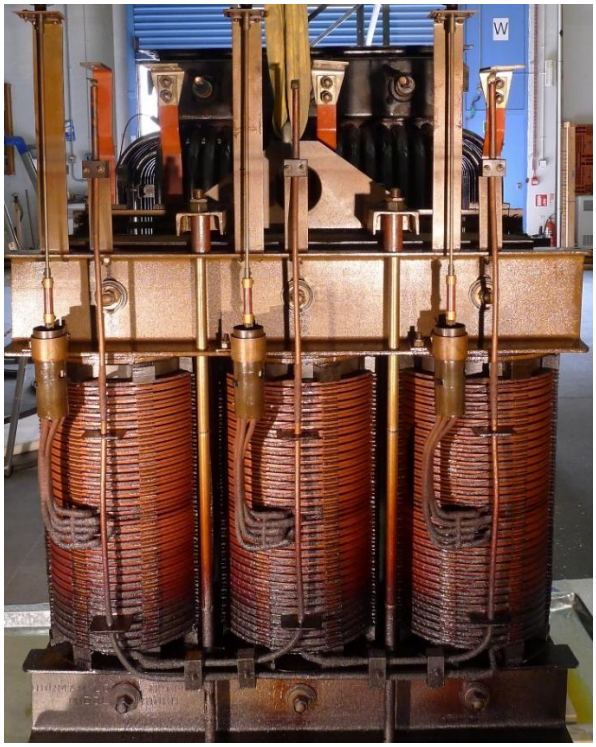


Figure 4-9 Front view of the core assembly of 6.4/0.4 kV DT

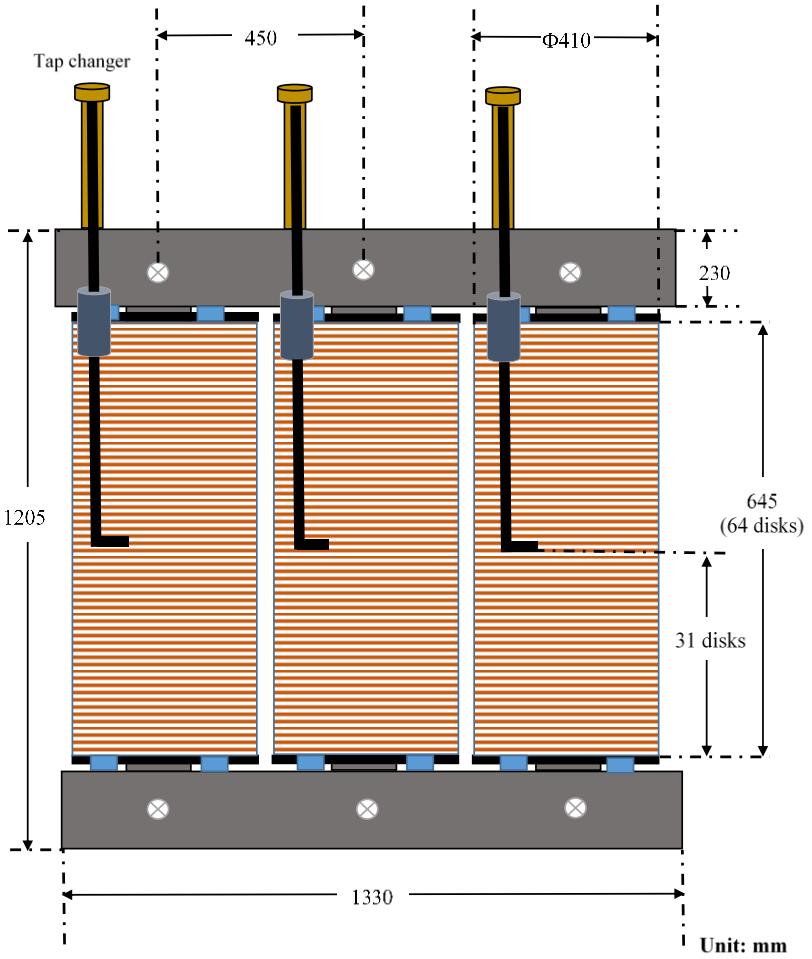


Figure 4-10 Dimensions of core and winding structure of 6.4/0.4 kV DT

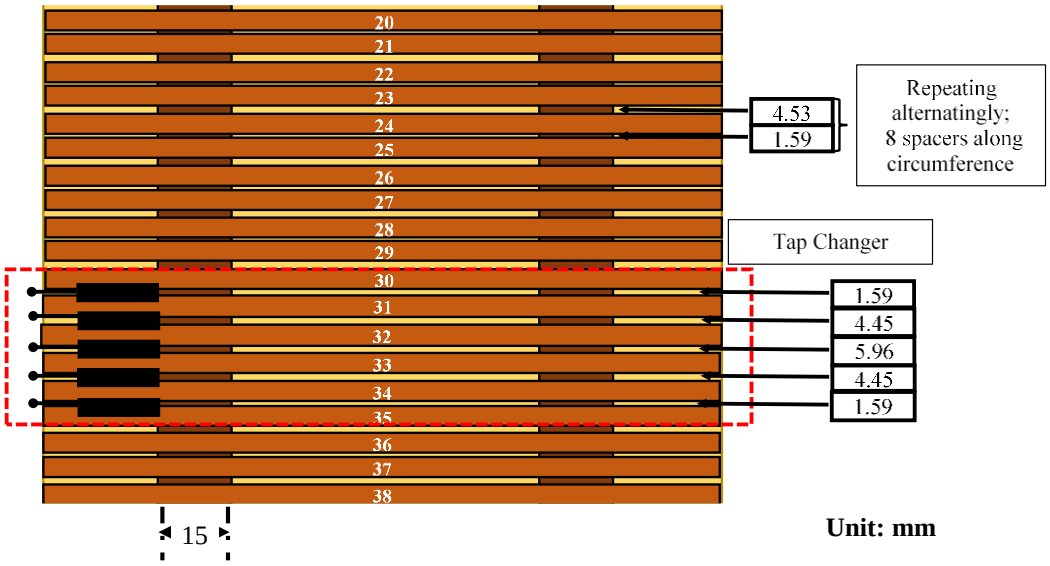


Figure 4-11 Dimensions of winding arrangement near the tap changer for 6.4/0.4 kV DT

After the physical inspection, samples of the winding were collected in order to measure the degradation state of paper insulation. Safety girders were provided on

the various locations of the winding as seen in Figure 4-12, to mitigate any risks of the windings falling apart during/after paper sampling.

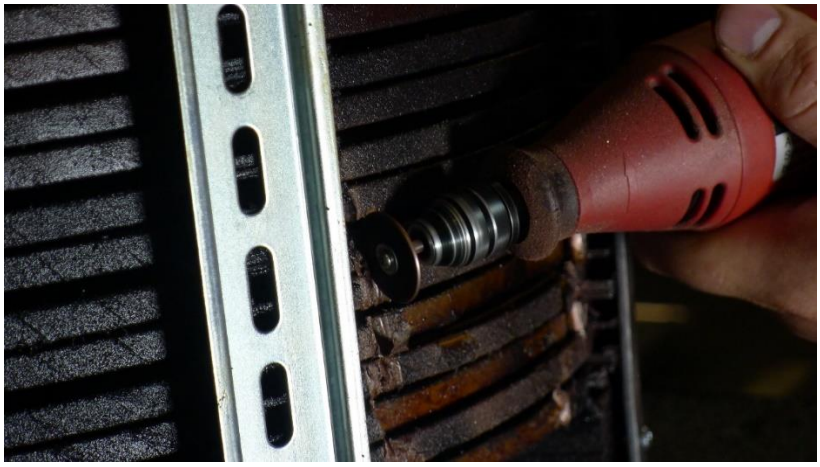


Figure 4-12 Girder arrangement for the winding of 6.4/0.4 kV DT

It was decided to use moisture in paper, LMA in paper, and Degree of Polymerisation (DP) of paper as the indicative parameters for the condition of the solid insulation. Profiles of these parameters along the winding were established prior to execution of the regeneration experiment. The windings were observed to have 2 layers of wrapped paper insulation, each with a thickness of 0.4 mm on an average.

The profile of moisture in the paper from the top to bottom windings is shown in Figure 4-13. The moisture across all discs was at a similar level of around 3.5% on average. This could be attributed to the prolonged duration of non-operation (approximately 18 months) of the transformer post-retirement, during which the system would have reached a state of equilibrium.

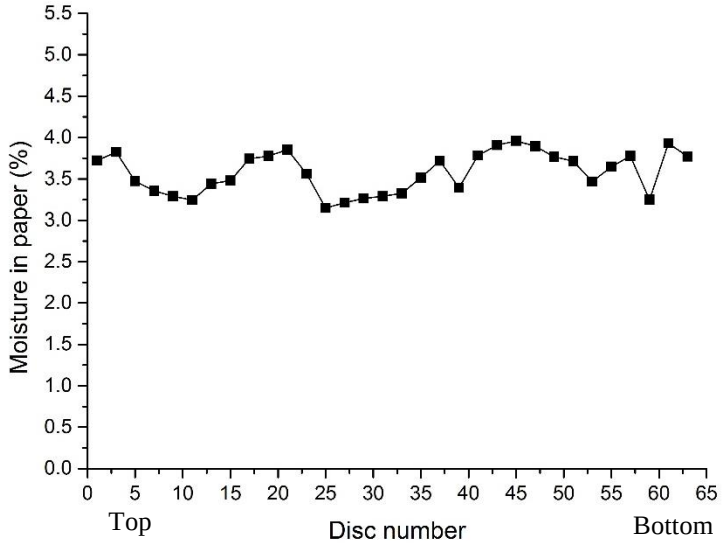


Figure 4-13 Profile of moisture distribution along the winding before oil regeneration

In contrast to the moisture, LMA in paper exhibited a clear profile from the top to the bottom of the winding, as seen in Figure 4-14. A higher LMA content of about 12.5 mg KOH/g was observed in the discs near the top of the winding, gradually reducing to lower values of around 8.5 mg KOH/g near the bottom of the winding. This trend could be explained by the thermal profile of the windings during operation, with the discs near the top experiencing a higher temperature than those near the bottom [111], leading to faster ageing. Average LMA content in the paper before oil regeneration was approximately 10 mg KOH/g.

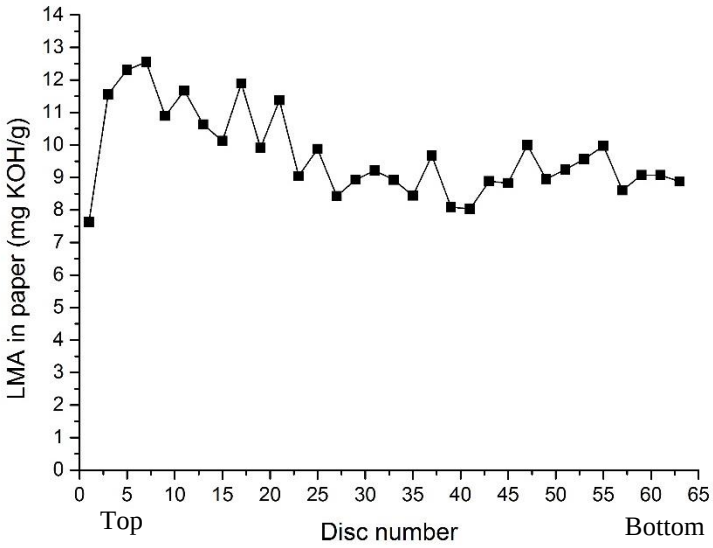


Figure 4-14 Profile of LMA distribution along the winding before oil regeneration

The value of LMA in paper is significantly higher than those previously reported in other investigations of in-service aged transformers [63]. For example, the oldest transformers reported by Azis [63] was 50 years old (in-service), with the highest LMA in paper content of around 6 mg KOH/g and lowest of 1.5 mg KOH/g.

DP is considered as an accurate indication of the mechanical strength of the paper. It was observed that the DP of the paper samples before regeneration was low, with an average value of 185. A DP value of 200 is regarded as an indication of the exhaustion of the mechanical strength of paper [9, 14, 112, 113], suggesting that the transformer has indeed reached end-of-life.

It is noted that the DP values exhibit an increasing trend from the top to the bottom of the winding as shown in Figure 4-15. This suggests a higher temperature near the top of the winding, which conforms to the LMA profile observed in Figure 4-14. The results of DP and LMA are in agreement with suggestions that the hot spot of the winding occurs near the top [111, 114].

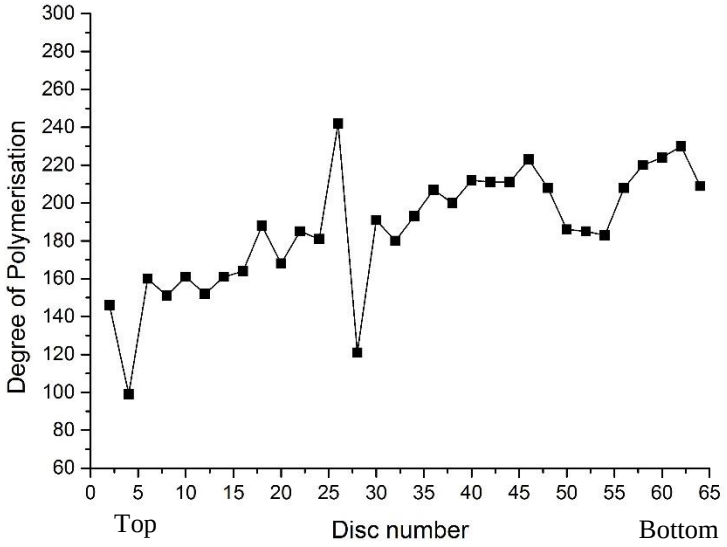


Figure 4-15 Profile of DP along the winding before oil regeneration

Figure 4-16 shows the relationship between DP and LMA in paper for this transformer. It is observed that the DP of the paper reduces as the LMA in paper increases, as suggested by previous studies [63, 109]. The scattered DP values measured at the 25th and 27th discs could be due to the presence of the tap changers near the sampling locations (as illustrated in Figure 4-11). Assuming the end-of-life criteria of paper to be a DP of 200, it is observable from the results that transformers with an LMA in paper of greater than 9 mg KOH/g would reach their physical end-of-life.

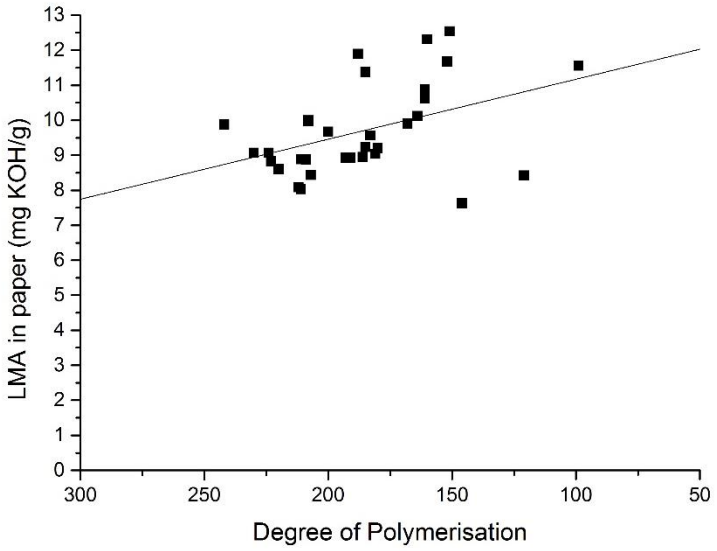


Figure 4-16 Relationship between Degree of Polymerisation (DP) and LMA in paper

4.4 Experimental Descriptions

Before commencing the oil regeneration experiment, temperature and moisture sensors were installed to facilitate on-line process monitoring. Laboratory-conditioned paper samples were installed to study the effect of the regeneration process on different initial conditions of paper insulation, which also served as back-up samples for the study. These samples were removed at different intervals during the process, along with paper samples from the windings, in order to analyse the changes to the moisture and LMA parameters due to oil regeneration.

4.4.1 Preparation of laboratory-conditioned paper samples

Four sets of pre-conditioned samples were installed near the windings. The aim of installing these samples was to control the initial parameters of the paper (moisture and acidity) in order to observe subsequent changes to the values during and after regeneration. Three different batches of paper were artificially conditioned to different values of initial moisture and LMA. A total of 8 layers of such paper were wrapped manually around a short PVC pipe to make one sample.

4.4.1.1 New, Dry Paper

New paper was dried in an air-circulating oven at 105 ℃ for 24 hours, followed by impregnation in new, dry mineral oil at 85 ℃ under vacuum for two days. The condition of the processed paper is shown in Table 4-7, where moisture content was 0.5% and LMA was 0.67 mg KOH/g on average, verified through multiple samplings.

4.4.1.2 Moisture conditioned paper

Dried paper samples were removed from the oil and transferred to a desiccator maintained at 50% Relative Humidity (RH). The samples remained in the desiccator for 3 days, at the end of which multiple samples from different locations within the desiccator were used to verify a uniform moisture content. The moisture conditioned samples had a final moisture content of about 6.5% on average. The LMA content of the paper was maintained at 0.75 mg KOH/g.

4.4.1.3 Aged paper

Dried paper samples impregnated in mineral oil were subjected to sealed ageing at 130 ℃ for a period of 2 weeks. A system consisting of 1000 ml oil, 70g paper and

100 cm^2 surface area of copper was used to age the paper to required levels of LMA in paper (around 4.64 mg KOH/g), elaborated in Table 4-7. Final moisture content in paper was 1.6%.

Table 4-7 Values of acidity and moisture for conditioned paper samples

Sample code	Description	LMA (mg KOH/g)	Moisture (%)
D	New, dry paper	0.67	0.5
M	New, moisture conditioned paper	0.75	6.4
A	Aged paper	4.64	1.6

4.4.2 Installation of the monitoring sensors and paper samples

In order to monitor the oil regeneration process on-line, it was decided to install temperature and moisture sensors at different locations inside the tank. The locations of the temperature and moisture sensors, and the laboratory-conditioned samples are presented in Figure 4-17 and Figure 4-18. A total of eight thermocouples and one moisture sensor were installed on the windings. The thermal sensors (K-type thermocouples) were installed in eight locations – seven on the front side, and one in the back. The eighth thermocouple installed at the centre of the back of the windings has not been represented in the figure. A Vaisala MMT330 solid state RH sensor was installed at the centre of the winding, with the aim of observing moisture conditions inside the tank during oil regeneration.

The paper samples were installed on the front side of the transformer active portion. A single set of samples consisted of each of the D, M and A samples. A total of four sets of samples were placed in two different locations on the transformer core – one near the top (between the Y and B phase) and one near the bottom (between the R and Y phase). These samples were labelled using the sequence *(Location)(Sample Code)(Sample number)*. The locations were coded as T for Top and B for Bottom, and the sample number as 1 or 2, referring to a unique sample in that position. Thus, if referring to the moisture conditioned samples installed near the top of the transformer winding, the corresponding labels would be TM1 and TM2.

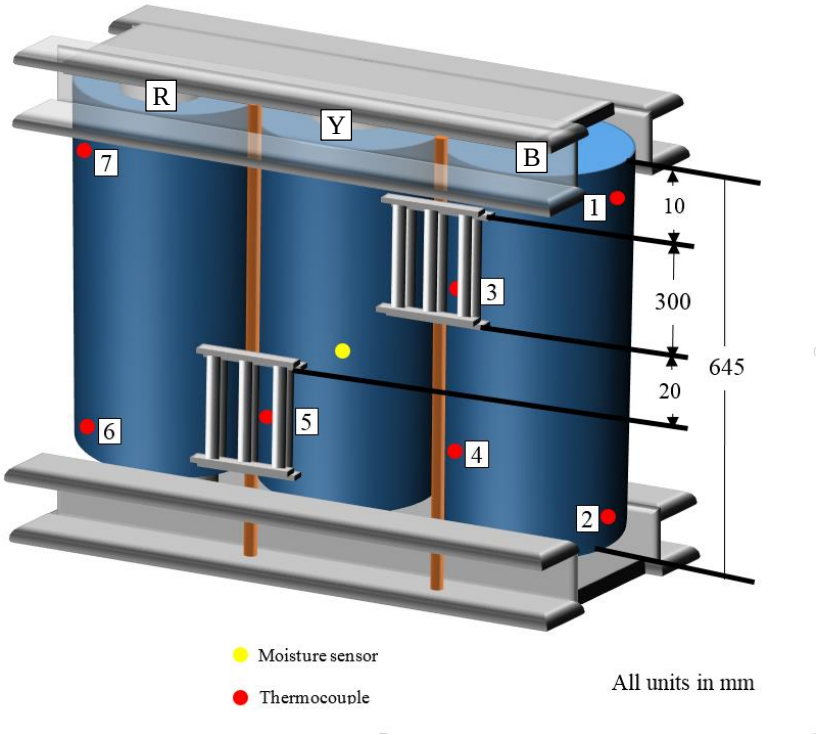


Figure 4-17 Location of the temperature sensors, moisture sensors and pre-conditioned samples

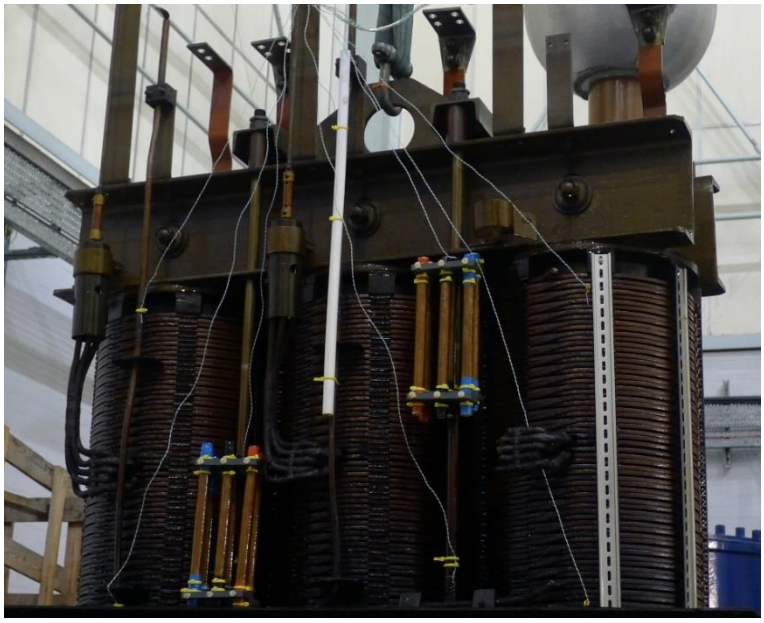


Figure 4-18 Front view of the active portion of the transformer, after installation of thermocouples, moisture sensor and pre-conditioned paper samples

4.4.3 Oil regeneration setup and procedure

The oil regeneration process can be split into three distinct processes – drying and degassing, filtering, and fuller's earth reclamation. A schematic diagram for the oil regeneration process is presented in Figure 4-19. The entire unit is operated through

a central control panel, with built-in safety elements and controllers, apart from being provided with a range of alarms and interlocks.

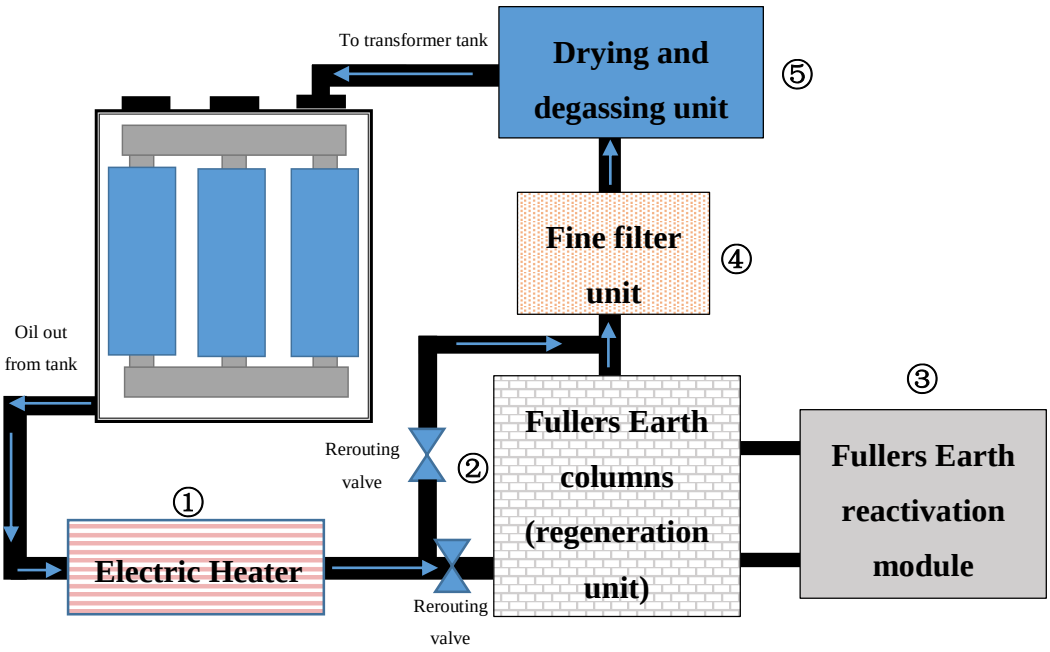


Figure 4-19 Schematic diagram of the oil regeneration system

4.4.3.1 Electric heater

Component ① in Figure 4-19 is a low watt density heater (max 1.7 watts/cm^2), which is used to increase the efficiency of the process by aiding easier spreading of the hot oil through the coalescers and filters. The heater is designed to heat the incoming oil up to a temperature of 90 ℃. The heating element also plays a key role in the removal of chemical ageing by-products, which is executed by the fuller's earth unit. The oil passes through a coarse inlet filter before entering the heater, designed to remove suspended particles of size larger than 80 μm.

4.4.3.2 Fuller's earth columns (reclamation unit)

Component ② of the setup is the central oil regeneration unit. This unit primarily consists of a single column of fuller's earth, which is the adsorbent medium for the chemical ageing by-product removal process. Oil which has been heated by the heater unit is pushed through the fuller's earth column, where the constituents contributing to acidity are gradually removed. These columns are reusable after saturation, through a process called reactivation.

4.4.3.3 Fuller's earth reactivation module

Component ③ of the regeneration setup is the fuller's earth reactivation module. Reactivation of the fuller's earth needs to be initiated manually, at the discretion of the operator. The process involved burning down the fuller's earth, along with all the adsorbed impurities. The oil present on the surface of the fuller's earth serves as fuel, and the burning is initiated by a coil present at the top of the column. The fuller's earth itself has an extremely high thermal capacity and does not get destroyed, despite temperatures within the columns reaching up to 700 ℃. The exhaust gases produced are passed through an activated carbon column, before being released outside into the atmosphere.

4.4.3.4 Fine filter unit

Component ④ of the setup consists of a primary fine filter to remove particles of size over 0.5 μm. The primary filters are constructed from non-migration type cellulose material featuring a large surface area and dirt folding capacity. These filters, once saturated, can be replaced easily.

4.4.3.5 Drying and degassing unit

The drying and degassing unit (Component ⑤) contains two coalescers, which are porous media cartridges, and operates under a vacuum of 5 mbar or less. The oil passes through layers of bonded fibreglass that constitutes the coalescers, where millions of sharp edges shear the oil, thereby exposing it to the effect of the vacuum. Water and other vapours are evacuated by the vacuum pump and exhausted. The equipment is designed to reduce the water content in the oil to be less than 5 ppm.

4.4.3.6 Connecting the oil regeneration system to the transformer

The setup for the oil regeneration experiment is shown in Figure 4-20. The outlet tap of the transformer is connected to the inlet of the oil processor unit through a hose. The first step of oil flow is through the heater unit, where the oil temperature is raised to required temperatures. The heated oil is then sent to the fuller's earth oil regeneration unit, through a rerouting valve installed on the processor unit. Once the oil passes through the fuller's earth column, it is then pumped back to the oil processor unit where it passes through the fine filter. Once the particle contaminant

has been removed, the oil passes to the drying and degassing unit (Component ⑤). The processed oil is then pumped back into the transformer through the outlet hose, which ejects the oil near the top of the transformer tank.

In the event of saturation of the fuller's earth column, the rerouting valve on the processor can be switched such that the oil flow to the fuller's earth unit is by-passed, allowing the commencement of the reactivation process. The oil processor unit operates continuously, while the fuller's earth unit operates between cycles of processing and reactivation.

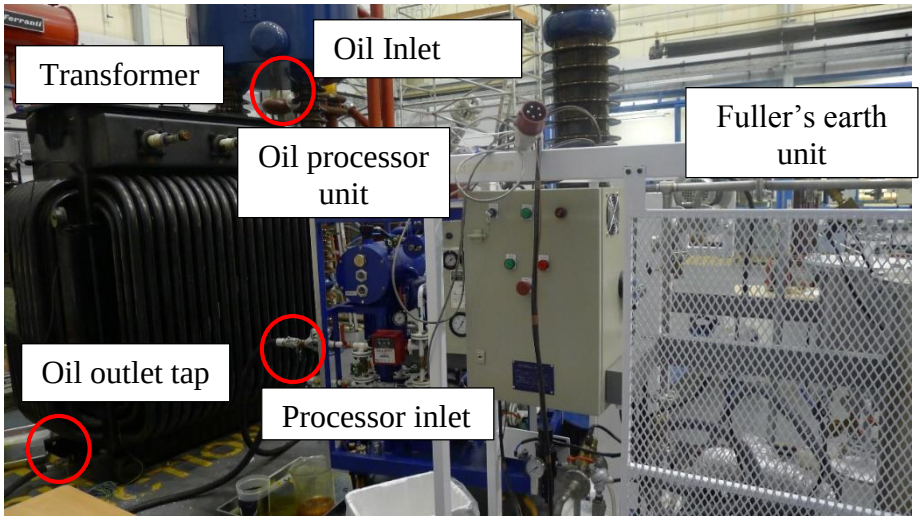


Figure 4-20 The setup for the oil regeneration experiment

Normal industrial practice comprises of conducting the oil regeneration till satisfactory values for the oil parameters are reached. Previous studies [5, 80, 84, 95, 101, 115] have mainly focussed on improving the condition of the oil and drying the paper insulation. In order to gain a deeper understanding of the effect of this process on the paper moisture and LMA, we chose to add an additional stage of processing beyond the 'cleaning' of the oil. Thus, the oil regeneration process was conducted over two stages, henceforth labelled Stage 1 and Stage 2.

a) Stage 1:

   This stage would be targeted at bringing down the acidity of the oil to levels specified in IEC 60296. The aim of this stage would be to investigate the effectiveness of the process on the oil, in reducing moisture and acidity. It was decided to execute this stage at a system temperature of about 60 ℃ within the transformer. The reduction of acidity in oil was used as the standard for determining the end of stage 1.

b) Stage 2:

The primary aim of this stage is to improve the condition of the paper through prolonged circulation. The system temperature in this stage would also need to be higher than that of stage 1, and greater than the aniline point of the oil in order to increase the solvency of the oil for the materials in contact with it. It was decided to execute this stage at a temperature of around 70 ℃ within the transformer.

The duration of stage 2 was set to be longer than that of stage 1 in terms of processing through the fuller's earth columns, considering the fact that any migration of acids and moisture from the paper into the oil would be extremely slow, and therefore require longer periods of circulation.

The capacity of the equipment used in this study is extremely low in comparison with industrial standards – an example would be the flow rate, which is in the range of thousands of L/h in commercial regeneration plants. Since this particular plant was designed for indoors laboratory use, the capacity only at 300 L/h, and with a single column of fuller's earth. The low capacity of the equipment used in this study is further emphasised in explaining the perceivably longer total duration of the experiment. It is noted that industrial equipment would be able to process at considerably higher rates, through multiple columns of fuller's earth, and with a relative ease of temperature control.

4.4.4 Sampling and measurements

Paper samples were collected from the transformer windings prior to the commencement of the regeneration process. Samples were later obtained from the windings after stage 1, and after stage 2 of the regeneration experiment from the same location and along the same disc numbers to facilitate comparison. One set of pre-conditioned samples (D, M and A) was also removed from each location at the end of stage 1 and stage 2 for testing. Pre-conditioned samples were handled manually during removal, using powder-free latex examination gloves. The samples were transferred to individual resalable zipper storage bags after removal from the harness.

Oil samples were collected regularly throughout the regeneration process. The sampling interval varied from one hour during the stage 1 to two hours during stage

2. Temperature at the time of sampling was also noted. Measurements of moisture were carried out on all samples collected throughout the experiment, and measurements of TAN were carried out on samples specifically collected during the operation of the fuller's earth regeneration unit.

TAN of oil, moisture in oil, moisture in paper and LMA in paper were measured as per the procedure detailed in Chapter 3. DP was measured using a Ubbelohde viscometer tube according to ASTM D4243. Specific viscosity of the paper was calculated by measuring the viscosity of paper and Cupreienthylene-diamine (Cuen) mixture. Intrinsic viscosity was then calculated based on specific viscosity and concentration of the solution, from which DP was calculated.

4.5 Results and Discussions

4.5.1 An overview of the process

The initial volume of oil in the transformer was estimated to be 900 L. The flow rate for the equipment was set at approximately 300 L/h. This would translate to a time period of 3 hours for a single pass of the entire volume of oil to be processed. The total duration of the regeneration experiment is given in Table 4-8.

Table 4-8 Operating time of the oil regeneration experiment

Process	**Duration (Hours)**			**Number of equivalent passes**		
	Stage 1	**Stage 2**	**Total**	**Stage 1**	**Stage 2**	**Total**
Filtration, drying and degassing	201	177	378	67	59	126
Regeneration	29	60	89	10	20	30

The profile of oil temperature during the regeneration experiment was obtained from the eight sensors installed on the transformer during the initial sampling stage, and is shown in Figure 4-21. P1 refers to the initial preparation stage, during which the experimental setup and operational performance were tested, and the oil was heated to required temperatures. Several mitigating factors are to be noted for the extended timescale through the filtering, drying and degassing unit. During the initial stages of the experiment, it was impossible to maintain complete vacuum in the processor due to excessive foaming. While this was expected, it resulted in the system operating at low vacuum for a considerable period of time. It can be seen that initial temperature rise stabilises at around 40 ℃, despite setting the temperature of the heater unit at

65 ℃. Thus, it was decided to wrap an insulating jacket around the transformer as shown in Figure 4-22, in order to reduce the heat dissipated to the environment. The oil temperature then reached satisfactory levels within a day. Point 'A' represents the time at which this jacket was installed, followed by a steady rise in temperature up to 60 ℃.

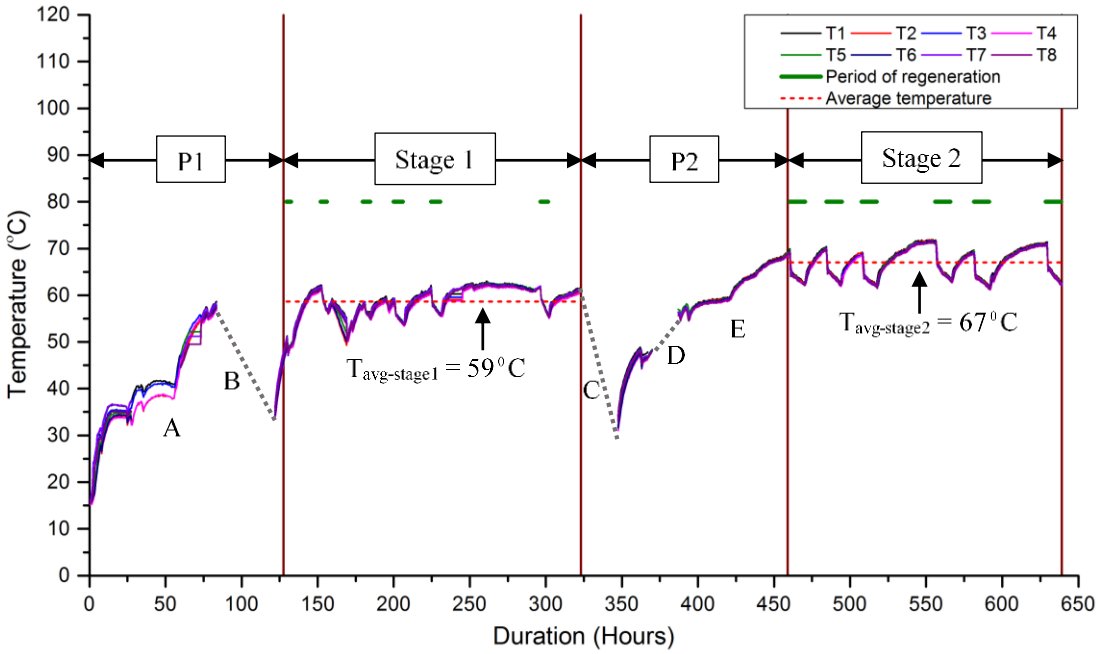


Figure 4-21 Temperature profile during the regeneration experiment

Figure 4-22 The transformer after being wrapped with insulating jacket

Region 'B' indicates a period of non-operation of the equipment due to an oil leak. The oil temperature dropped to around 35 ℃ when this issue was fixed, following which the system was restarted.

Stage 1 was initiated once the oil had reached satisfactory temperatures, and lasted a total of 201 hours, as detailed in Table 4-8. The average oil temperature during this period was maintained at 59 ℃. A total of 6 regeneration cycles were performed during Stage 1, lasting a total of 29 hours equivalent to approximately 10 passes of the entire volume of the oil through the fuller's earth column.

Reactivation of the fuller's earth is a lengthy process, taking between 7 and 10 hours. Thus, it was only possible to run the regeneration plant for several hours a day before reactivation. However, the oil processor unit had to be operated continuously throughout the day in order to maintain the oil temperature within the transformer.

P2 refers to the intermediate preparation stage. This stage started with the sampling of winding paper and removal of one set of laboratory-conditioned samples (represented by 'C' in Figure 4-21). During the sampling, the equipment was switched off completely and the temperature fell gradually to around 30 ℃. After sampling, the oil was circulated through the heater to raise the oil temperature to around 70 ℃ for stage 2 – 10 ℃ higher than stage 1. The missing temperature data during 'D' was due to an instrument error. It was observed that the temperature saturated at 60 ℃, the same temperature as stage 1. Since it was aimed to increase the oil temperature to 70 ℃, the temperature setting on the heater was increased to 85 ℃ at 'E' on Figure 4-21. This helped increasing the oil temperature to an average of 70 ℃ before the start of stage 2.

Stage 2 of the oil regeneration experiment was conducted for a period of 177 hours, as detailed in Table 4-8. This stage included 6 cycles of regeneration which are 60 hours of circulation through the fuller's earth column. The oil temperature was at an average of 67 ℃ during stage 2. The fluctuating temperature pattern in both stage 1 and stage 2 is attributed to heat loss during circulation through the Fuller's earth column. The reduced duration of filtering, drying and degassing in stage 2 in comparison with stage 1 is attributed to the low value of acidity of the oil during stage 2, enabling extended circulation through the fuller's earth without everyday reactivation.

4.5.2 Oil parameters

4.5.2.1 Acidity in oil

The trend for oil acidity during stage 1 and stage 2 of oil regeneration is presented in Figure 4-23. Oil acidity was measured for the samples collected during the period which the circulation was routed through the fuller's earth unit. The reduction in acidity levels of the oil formed the basis for deciding the end of stage 1 of the oil regeneration experiment. It was anticipated that the oil acidity would reduce to low levels of around 0.05 by the end of stage one, as this value represents the expected acidity range of new mineral oils. This value was reached within 29 hours (approximately 10 passes) of circulation through the fuller's earth regeneration unit.

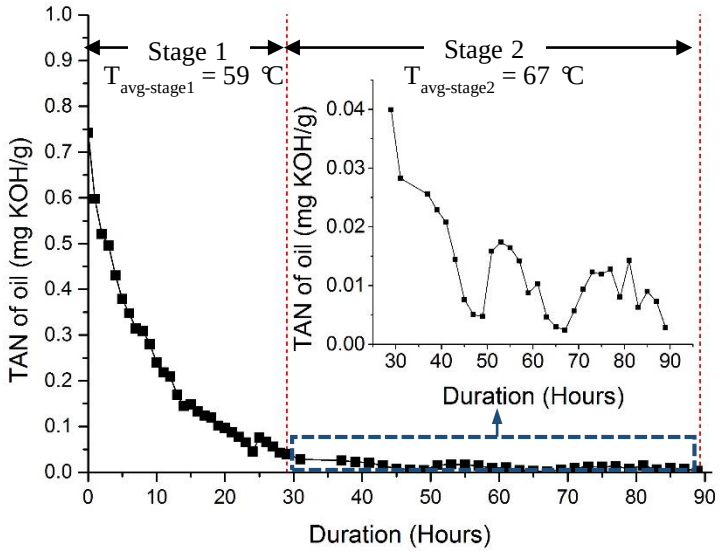


Figure 4-23 TAN of oil profile during the regeneration experiment

It can be observed from Figure 4-23 that the reduction trend for TAN follows a negative exponential relationship with duration. The fluctuations of the TAN during stage 2 could be further indication of the removal of the acidic components from the paper. These results conform to previous studies, which indicated similar fluctuations of TAN values [7]. TAN trend during stage 2 of regeneration indicates that the final TAN value for oil was near 0.005 mg KOH/g. This value is extremely low, even in comparison with certain new oils.

4.5.2.2 Moisture in oil

The profile of moisture in oil during stage 1 and stage 2 of oil regeneration are presented in Figure 4-24. Moisture in oil was observed to have reduced to be less than 10 ppm at the end of stage 1, and remained in the same level till the end of stage

2. Up to a duration of 75 hours, the moisture in oil was observed to fluctuate between 15 ppm and 35 ppm. This fluctuation is possibly due to mixing of water content distributed in the transformer tank, which could vary from the bottom to the top. From 75 hours onwards, the oil moisture gradually reduced to around 10 ppm by the end of stage 1. During stage 2, the oil moisture was again observed to fluctuate between 6 ppm and 14 ppm, which could indicate removal of moisture from the paper.

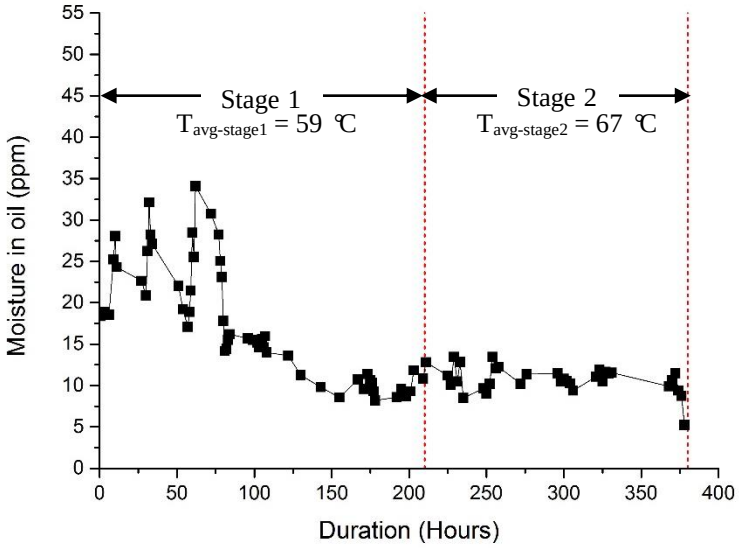


Figure 4-24 Moisture in oil profile during the regeneration experiment

A comparison of the moisture measured using KF titration and the moisture values calculated by the solid state sensor based on RH is provided in Figure 4-25. RH values and subsequent moisture calculations, along with the oil temperatures, are represented in intervals of 30 minutes, whereas the values of moisture measured through KF are based on samples collected during the day in intervals of every 2 hours on an average. Figure 4-25 indicates a reasonable correlation between the values recorded by the RH sensor and those measured by KF titration. It is noted that the moisture in oil measured through RH sensor does not consider the change in saturation level of the oil when it is aged, and thus these values are marginally lower than the moisture measured by KF titration. The gradual reduction of the RH value is a clear indication of the continuous drying of the oil throughout the process.

Overall, the trend of moisture in oil followed the temperature during stage 2, with higher moisture content accompanying a higher oil temperature. This could be attributed to the higher saturation levels of oil at higher temperatures, allowing for a greater transfer of moisture from the paper to the oil.

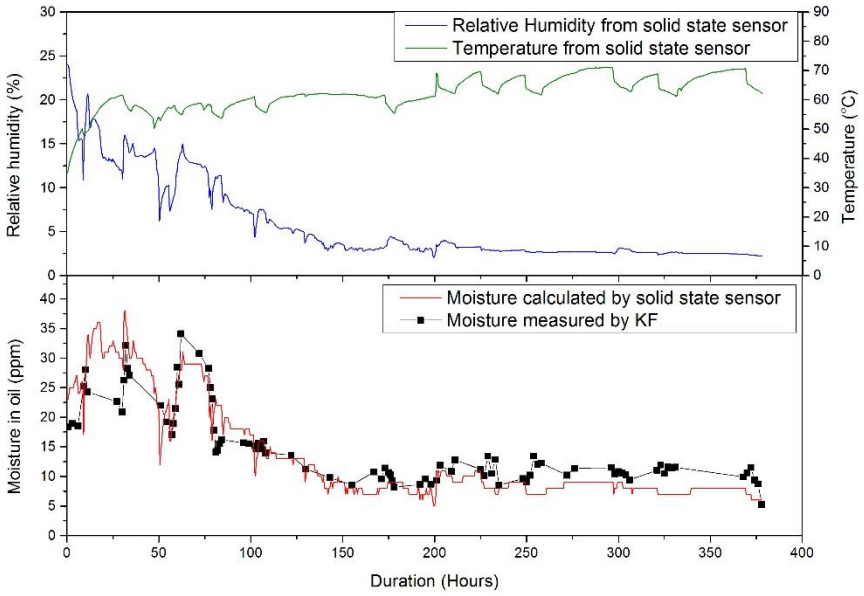


Figure 4-25 Comparison of moisture in oil measured by KF titration and moisture in oil measured by solid state sensor, along with oil relative humidity and temperature

4.5.3 Paper parameters

4.5.3.1 Moisture in paper

Moisture in paper profiles for samples collected before oil regeneration, at the end of stage 1 and the end of stage 2 are presented in Figure 4-26. Initial moisture level in the paper before oil regeneration was 3.5% on average, exhibiting a flat trend from the bottom to the top of the winding. At the end of stage 1, this value was observed to have reduced to an average of 2.7%, which represents a 23% reduction. This value further dropped to 2.1% at the end of stage 2, a further 23% reduction from the value at the end of stage 1, and a net reduction of 40% from the original average moisture value. Interpreting this reduction along with the various experimental and simulation-based drying curves and models proposed in the literature [5, 6, 74, 75, 77, 88, 95, 116], it is possible that the moisture could reduce further with prolonged circulation. However, several factors could affect this, including the limitation of the off-line hot oil circulation process in not heating the insulation from inside (i.e. affecting mainly the outer layers of insulation), and the thickness of the paper which directly affects the penetration of the drying. From Figure 4-26, it is observed that the reductions in moisture values are much greater in the bottom discs, at the end stage 1 and stage 2.

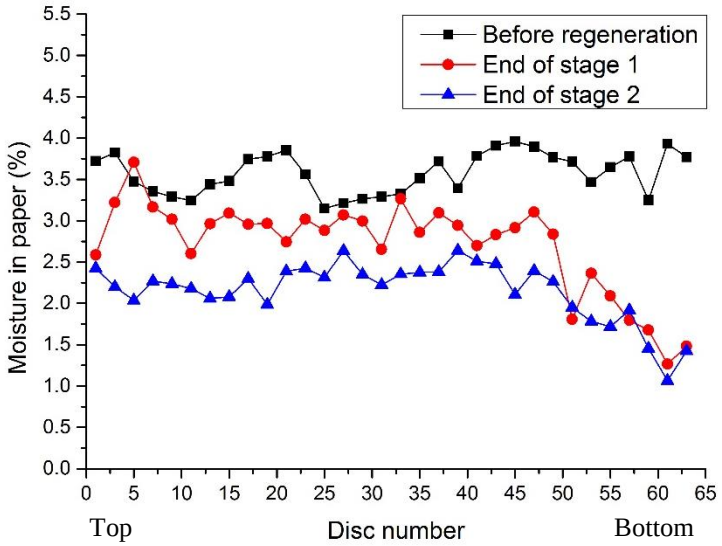


Figure 4-26 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2

4.5.3.2 LMA in paper

Figure 4-27 illustrates the profile for LMA in the paper for samples collected before regeneration, at the end of stage 1, and the end of stage 2 of the regeneration experiment. Initial LMA in paper before oil regeneration was found to be at an average of 10 mg KOH/g. The LMA in paper remained fairly constant at the end of stage 1. However, at the end of stage 2, this value reduced to an average of 7 mg KOH/g. This is a positive indication of the effectiveness of stage 2 in improving the condition of the paper insulation.

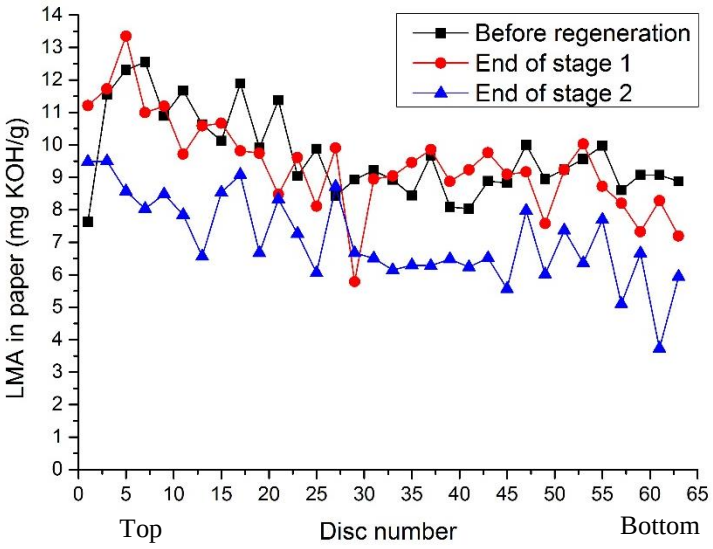


Figure 4-27 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2

In an investigation of the acid removal during LFH drying process [93], it was observed that LMA in paper dropped by approximately 20-30%, which was measured in paper samples collected before and after the drying process. This value conforms to the reductions observed in the present study, which were approximately at 30%.

4.5.3.3 Degree of Polymerisation (DP) of paper

In order to verify that the DP values are not affected by the extended circulation of hot oil through the transformer, samples of paper from 5 different locations along the winding were tested post-regeneration. No noticeable changes to the DP values were observed, as seen in Figure 4-28.

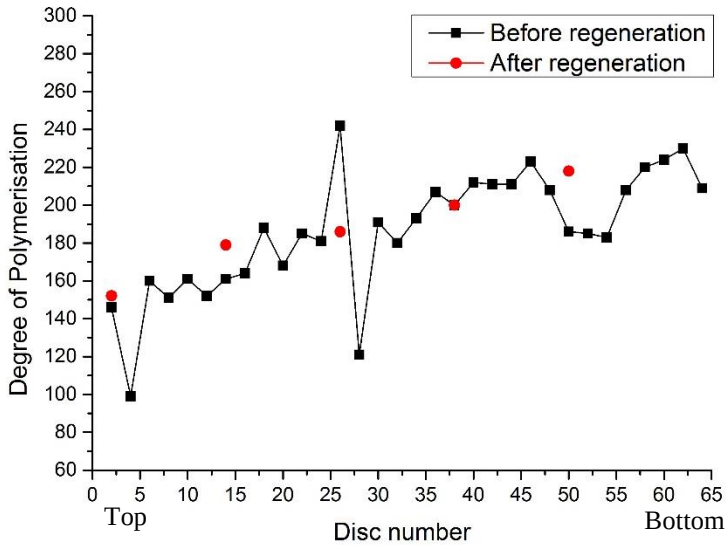


Figure 4-28 Profile of DP of paper before regeneration, and at the end of stage 2

4.5.4 Laboratory conditioned samples

4.5.4.1 Conditioned samples with high moisture in paper

Moisture in paper profile for the laboratory conditioned samples before regeneration, at the end of stage 1, and the end of stage 2 for the TM and BM samples are presented in Figure 4-29 and Figure 4-30 respectively. The moisture conditioned samples had an initial moisture content of 6.5% throughout all layers ,which reduced to around 3% at the end of stage 1 in the TM samples (Figure 4-29), and 3.5% for the BM samples (Figure 4-30) . At the end of stage 2, these values further reduced to an average of about 2.2% in both cases. Net reduction in moisture of the paper samples varied among layers. The average reduction in moisture for the laboratory conditioned samples at the end of stage 2 was approximately 65%, while the average reduction

for the transformer paper was merely 40% at the end of stage 2. This could be due to the considerably higher thickness of the transformer paper (approximately 0.4 mm) when compared to the paper used in the model (0.05 mm). Thus, the thickness of two layers of the paper on the transformer winding would be twice the net thickness of the paper model, resulting in a longer drying time.

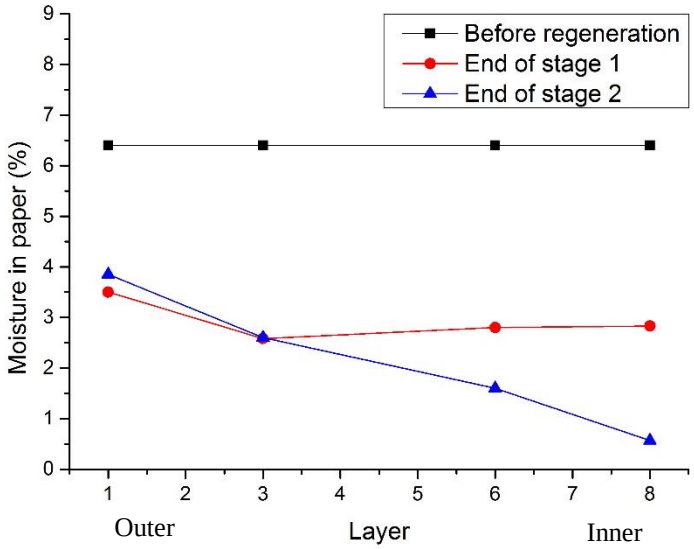


Figure 4-29 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2 for TM sample

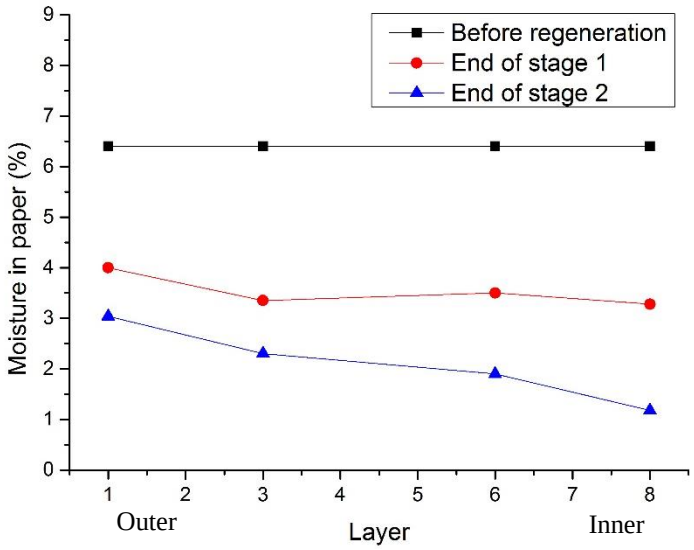


Figure 4-30 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2 for BM sample

It is noted that the reduction in moisture in the laboratory conditioned samples is in agreement with the reduction in moisture in the samples collected from the transformer windings at the end of stage 1 and stage 2 of the regeneration experiment. However, it is seen that the reduction in moisture of the laboratory conditioned

samples during stage 2 is neither apparent, nor uniform. The reason behind this profile is unclear. It is noted that the laboratory-conditioned samples were installed on separate physical models, and that the regeneration process and oil flow distribution could have had slightly different effects on these models.

Foss et al. [69] investigated the effect of the Vacuum Hot Oil Spray (HOS) process of drying by installing paper models comprising 50 layers of kraft paper in a new 93 MVA transformer before its commissioning. After 210 hours of drying time, the investigators reported a reduction in moisture in the outermost layer of paper from 2.43% to 0.96%. This indicates a 60% reduction in moisture in paper, compared to the TM sample in our study (Figure 4-29) where a mere 30% reduction in moisture in paper was observed at the end of stage 1, which lasted an approximate duration of 200 hours. However, this comparison may not be a clear indicator of the efficacy of the two process since the technique used for preparing the paper model and the dryout procedure used are different.

Layer effect in distribution of moisture is unclear in the samples at the end of stage 1, and visible at the end of stage 2 where the inner layers exhibit a lower moisture content than the outer layer of paper. It is possible that this effect occurred due to several reasons, including the re-adsorption of moisture by the paper samples after the regeneration process was stopped, and the sample preparation procedure which would have affected the initial moisture and the tightness of the layers.

In case of the aged and dry samples, the initial moisture was low. However, the moisture in the paper had increased due to prolonged immersion in oil with a high moisture content. These results are given in Appendix B.

4.5.4.2 Conditioned samples with high LMA content

LMA in the conditioned paper samples was measured before the regeneration process, at the end of stage 1, and the end of stage 2. The results for the TA and BA samples are presented in Figure 4-31 and Figure 4-32 respectively. The initial LMA in the laboratory-aged samples was 4.6 mg KOH/g. This value did not significantly change at the end of stage 1 in case of the TA sample. The LMA in paper exhibited a small reduction in the BA sample at the end of stage 1, to an average of around 3.7 mg KOH/g (approximately a 20% reduction from the initial value). At the end of

stage 2, these values drop to an average of 3 mg KOH/g (around 35% reduction from the initial values) in the TA sample and remained at 3.7 mg KOH/g for the BA samples.

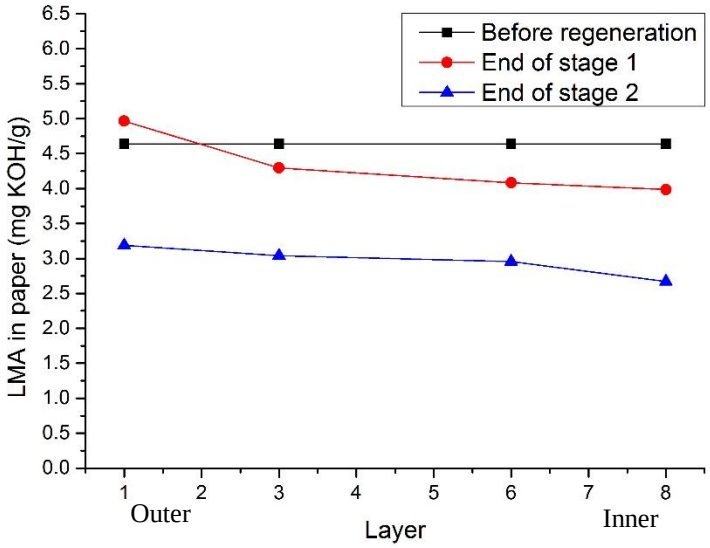


Figure 4-31 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2 for TA sample

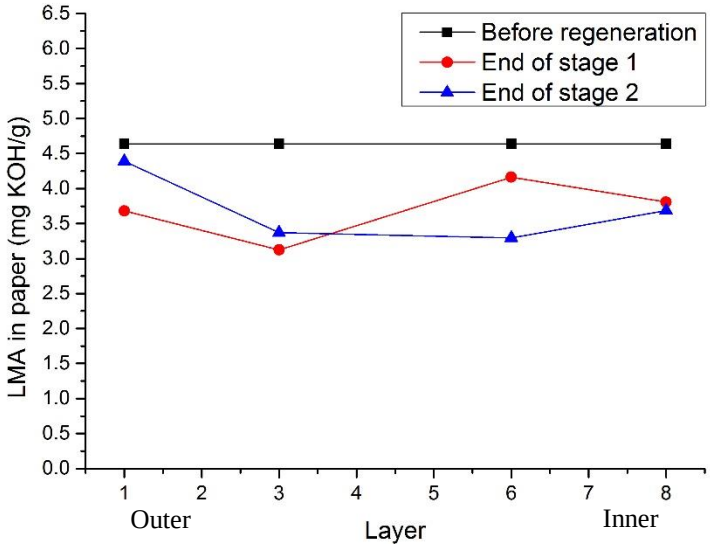


Figure 4-32 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2 for BA sample

The profile of LMA was observed to be nearly flat along all the layers of the sample. It is noted that the net reduction in LMA in paper is comparable to the reductions observed in the paper samples obtained from the transformer windings (30% reduction in LMA at the end of stage 2).

In case of the moisture conditioned and dry samples, the initial LMA was low. However, the LMA in paper had increased after prolonged immersion in oil with a high acidity. These results are shown in Appendix B.

4.5.5 Impact of the improved paper condition on the transformer life

In 1948, Daikin [117] premised that the ageing rate of the insulation was a chemical phenomenon. He proposed that the Arrhenius reaction rate theory is applicable to the deterioration of insulation, and could be modelled as

$$k = A \cdot e^{\left[-\frac{E_A}{R(T+273)}\right]}, \tag{4-1}$$

where A is the pre-exponential factor, E_A is the activation energy, R is the gas constant (8.314 J /K/mol), and T is the temperature of the paper in degree Celsius. Proposed values for the activation energy have varied from 76 to 150 kJ/mol [118, 119]. More recently, CIGRE Working Group A2.24 [8] recommended values of activation energy which are widely accepted, as summarised in Table 4-9. Provisional values for the pre-exponential factor A were also proposed by the same working group, as given in Table 4-9 [8]. These values can be used to extrapolate the values of A for other moisture contents in paper, as shown in Figure 4-33 [120].

Table 4-9 Pre-exponential factor and Activation energy as proposed by CIGRE WG A2.24 [8]

Parameter	**Oxidation**		**Hydrolysis**	
	Dry, no oxygen	**Dry, oxygen access**	**1.5% water in paper**	**3.5% water in paper**
E_A **(kJ/mol)**	128	89	128	
A **(hour^{-1})**	$4.1*10^{10}$	$4.6*10^{5}$	$1.5*10^{11}$	$4.5*10^{11}$

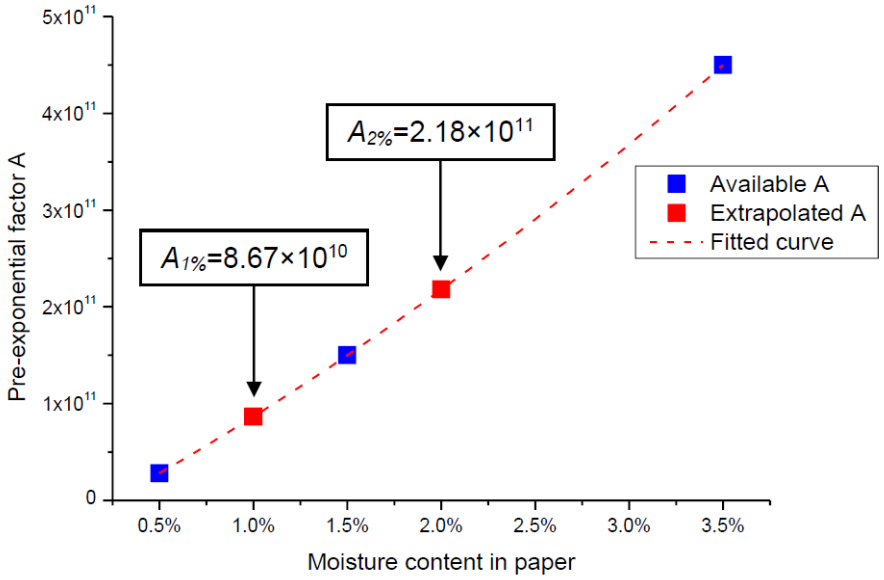


Figure 4-33 Extrapolation of the pre-exponential factor *A [120]*

Activation energy describes the temperature dependency of the ageing process. For hydrolysis, the ageing rate doubles every 7 ℃ [8]. On the other hand, *A* represents the influence of paper conditions. The *A* parameter depends heavily on the moisture content of the paper, and correlations between the value of *A* and moisture in paper have been presented by investigators in literature [121]. *k* represents the ageing rate of the paper insulation, and is related to the life of the transformer as follows:

$$k \cdot t = \frac{1}{DP_t} - \frac{1}{DP_o} \tag{4-2}$$

In equation 4-2, *t* refers to the time required to reduce the DP of the paper from a value DP_o to DP_t. DP_t is usually set at 200, which is believed to represent the end of life of paper [9, 14].

In order to study the effect of reduction of paper moisture on the residual life of the transformer, the change to the ageing rate *k* can be calculated, which would directly influence the life of the asset. Considering the change in moisture value from an initial moisture in paper of 3.5% before regeneration to a moisture content of 2% post-regeneration, the value of *A* would reduce from $A_1 = 4.5 \times 10^{11}$ hour^{-1} for 3.5% moisture in paper to $A_2 = 2.2 \times 10^{11}$ hour^{-1} for 2% moisture in paper. This represents a reduction in the ageing rate *k* by 50% using equation 4-1.

Similarly, assuming a reduction in paper moisture of 1% through oil regeneration, i.e., a post-regeneration moisture content in paper of 2.5%, the value of *A* would

reduce from $A_1 = 4.5 \times 10^{11}$ hour^{-1}, to $A_2 = 3 \times 10^{11}$ hour^{-1}. This still represents a 33% reduction in the ageing rate k of the transformer. In considering a third extreme scenario of a mere 0.5% reduction in moisture in paper through oil regeneration, the value of A would reduce from $A_1 = 4.5 \times 10^{11}$ hour^{-1}, to $A_2 = 3.5 \times 10^{11}$ hour^{-1}, indicating a 22% reduction in the ageing rate k using equation 4-1. Hence, according to the currently accepted ageing model, even a fractional reduction in the moisture content of the paper contributes significantly to reducing the ageing rate of the paper.

It is noted that the value of A parameter has so far been correlated solely to the moisture content of the paper, and all literature-reported models account only for reduction in this moisture content in the lifetime estimation of the transformer [32]. In addition, it is shown that LMA content of the paper also affects ageing rate of the paper insulation. However, there is a lack of quantitative correlation between the LMA in paper and the ageing and life estimation models.

Finally, given the relationship between the ageing rate k and the residual life of the transformer t, it is possible to roughly estimate the life extension achieved through the oil regeneration experiment through equation 4-2. For example, considering the scenario where the moisture content in paper reduces from 3.5% before regeneration to 2.5% after oil regeneration and assuming an initial residual life of the transformer as 10 years, the new residual life due to the reduction of the ageing rate by 50%, would be 15 years, which equals to an asset life extension of 5 years.

4.6 Summary

The effect of oil regeneration on the condition of the oil was observed through the monitoring of key parameters including TAN and moisture. Investigations into the condition of the paper revealed an obvious reduction of LMA and moisture values, which are regarded as key ageing accelerators for paper, was achieved after the oil regeneration process. DP indicated no change after the regeneration process, which indicates that the circulation of hot oil for extended periods of time does not cause any damage to the paper.

In addition, laboratory conditioned paper samples placed into the transformer prior to the experiment also indicated obvious improvements in terms of LMA and

moisture values, implying the effectiveness of the regeneration process in improving the paper conditions.

It is concluded that strong evidence has been provided to support the premise that oil regeneration can indeed positively affect the health conditions of the transformer oil-paper insulation system. Estimation through literature-reported ageing equations and models also provided substantial confirmation of a reduction in the ageing rate of the insulation and consequent extension of asset life post-oil regeneration.

Chapter 5. Conclusions and Future Work

5.1 Conclusions

This thesis presents a study of oil regeneration, a transformer intervention technique aimed at improving the oil and paper insulation conditions through the removal of the chemical by-products of ageing. Effectiveness of transformer oil regeneration was examined through laboratory accelerated ageing experiments and real-time application on a 77-year-old retired distribution transformer.

The long term performance of regenerated oil was studied utilising samples obtained from a previous on-site regeneration of a 44-year-old transformer. It was found that the performance of the oil after regeneration was better than the oil before regeneration. Further, it was observed that the performance of the oil after regeneration was even comparable to that of new oils. TI of the paper aged in oil after regeneration was found to reduce at a slower rate in comparison with paper aged in oil before regeneration, which support the premise that the oil condition is a factor in determining the ageing rate of the paper. It was also concluded that oil regeneration could contribute towards slowing down the ageing rate of paper in a transformer.

Oil regeneration was performed on a 77-year-old retired 6.4/0.4 kV distribution transformer in two stages (stage 1 and stage 2), the first aimed at ‘cleaning’ the oil and the second aimed at ‘cleaning’ the paper. Through the regular monitoring of oil parameters during the process, it was observed that the oil properties showed significant improvement in terms of TAN and moisture, with the final values of these properties being comparable to those of new oils. Paper samples were obtained from the transformer before oil regeneration, at the end of stage 1, and at the end of stage 2 of oil regeneration. It was observed that moisture in paper showed significant reductions by approximately 23% at the end of stage 1 and a further 23% at the end of stage 2, while LMA in paper exhibited no reductions at the end of stage 1 and an average reduction of 30% at the end of stage 2. These results were also verified using laboratory-conditioned paper samples installed in the transformer before the process, which confirmed reductions in moisture and LMA values for paper.

Overall, it was concluded that oil regeneration has a positive effect on improving the condition of the transformer oil-paper insulation system under investigated conditions. The need for an extended stage (stage 2) of the oil regeneration in addition to the conventional stage (stage 1) is stressed, in order to effectively improve the paper conditions. As the paper condition is improved, the ageing rate of the paper would be reduced, which could consequently extend the transformer life. Employment of oil regeneration could help utilities to defer asset replacement investment.

5.2 Future Work

The investigation in this work employed an equipment designed especially for indoor laboratory use, and therefore came with its own restrictions like the low speed of regeneration. Thus, there is a need to verify these findings with comprehensive industrial scale testing in order to find out the optimal oil regeneration procedure in terms of flow velocity, oil temperature and processing duration. Furthermore, all the findings in this work were based on laboratory experimental work, there is a need for a model to evaluate the effect of life extension of the transformer achieved through oil regeneration. .

The ageing experiments conducted in this study utilised systems consisting of only new paper to study the performance of oil after regeneration. While these ageing experiments confirm the better performance of oil after being subject to oil regeneration procedure, they can be further extended utilising systems of oil and service-aged paper. This would enable more comprehensive comparison of the long-term performance of paper when the transformer is subject to oil regeneration process, and aid in a more accurate estimation of life extension achieved through the procedure.

With substantial proof of the positive effect of oil regeneration on improving the oil and paper conditions of the transformer, the next step would be to test the long-term performance of this intervention technique on an in-service transformer. Regular monitoring of the oil parameters for a period of time post-oil regeneration can confirm the long term effects of oil regeneration on the ageing rate of the transformer. These studies can also be carried out alongside similar transformers which have not

been subject to oil regeneration and those which have undergone oil replacement, in order to enable comparison.

Ageing models proposed in the past rely upon the paper condition to predict the remnant life of the asset. However, these models solely incorporate the moisture content in the paper and DP of paper as the indication of the ageing state. Recently, the effect of LMA on the ageing of the oil-paper insulation system was proposed. Thus, there is a need to quantify the effect of LMA on paper ageing and incorporate it in the aging model.

Appendix A. Electrical Testing of 6.4/0.4 kV Transformer

PD measurements during ACSD test of 6.4/0.4 kV transformer

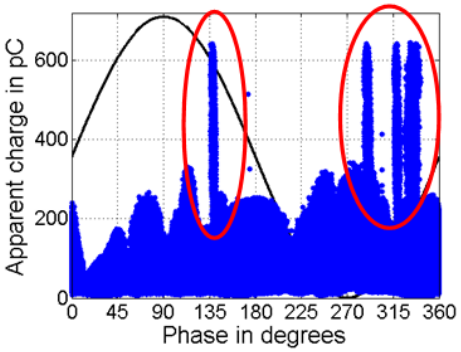
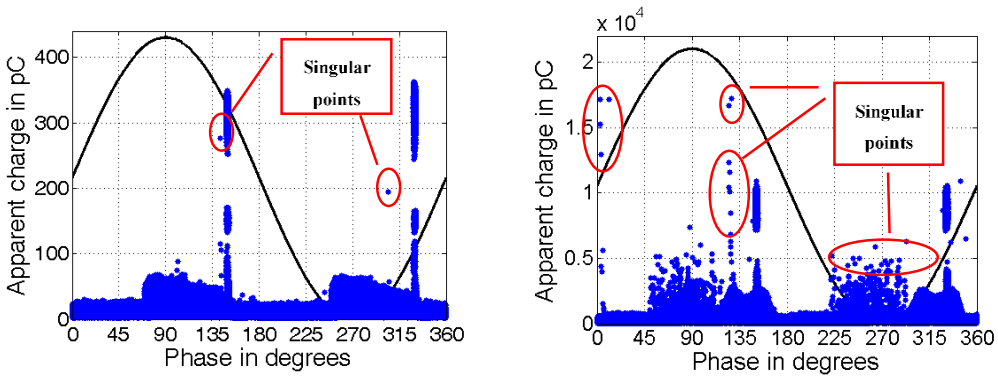
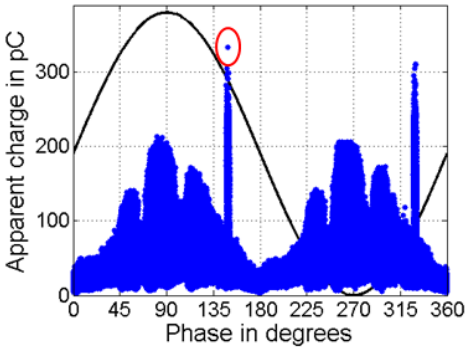


Figure A-1 PRPD pattern of background noise for 6.4/0.4 kV DT

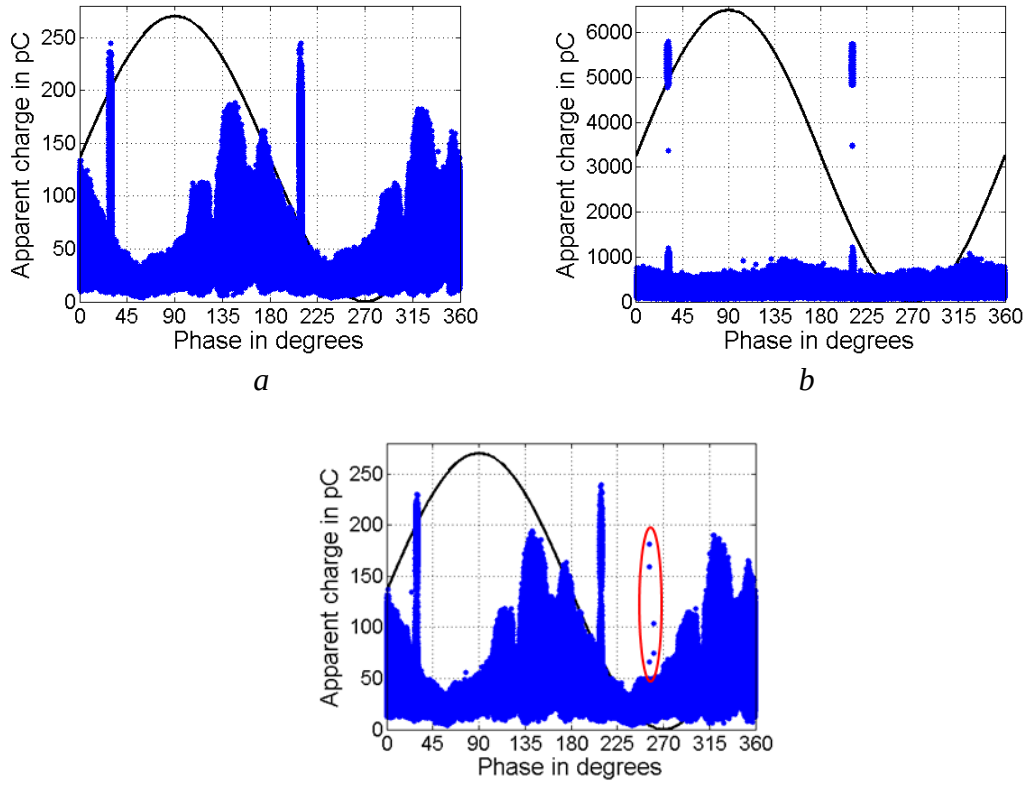


a *b*



c

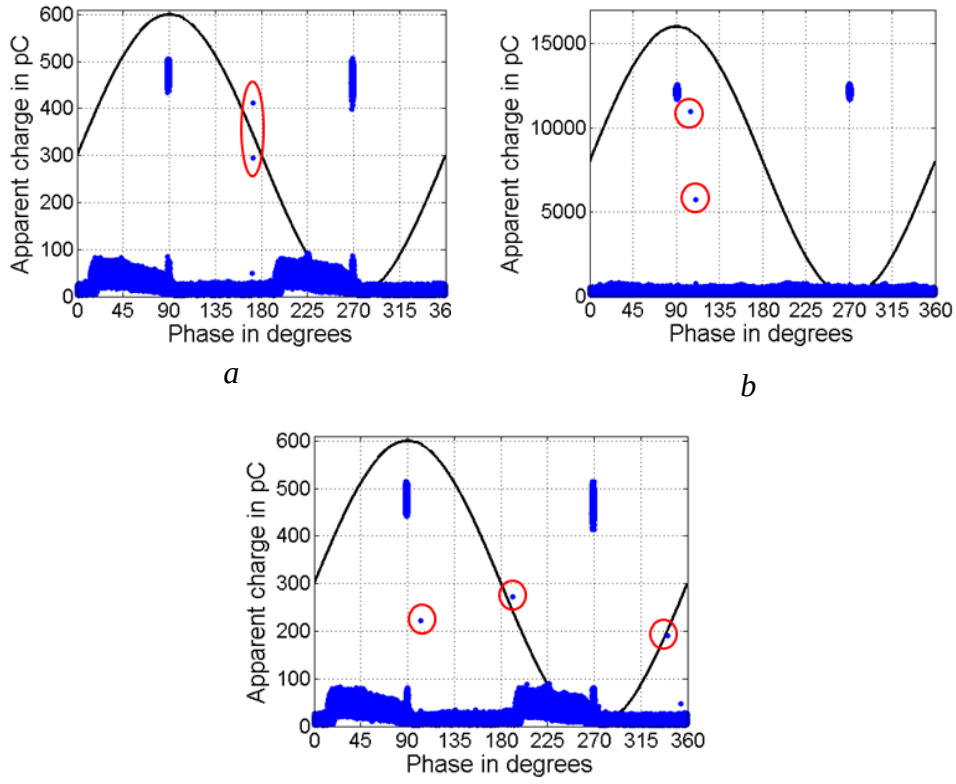
Figure A-2 PRPD patterns of R_{HV} phase at a) 3.2 kV, b) 6.4 kV and c) 3.2 kV return for 6.4/0.4 kV DT



a *b*

c

Figure A-3 PRPD patterns of Y_{HV} phase at a) 3.2 kV, b) 6.4 kV and c) 3.2 kV return for 6.4/0.4 kV DT



a *b*

c

Figure A-4 PRPD patterns of B_{HV} phase at a) 3.2 kV, b) 6.4 kV and c) 3.2 kV return for 6.4/0.4 kV DT

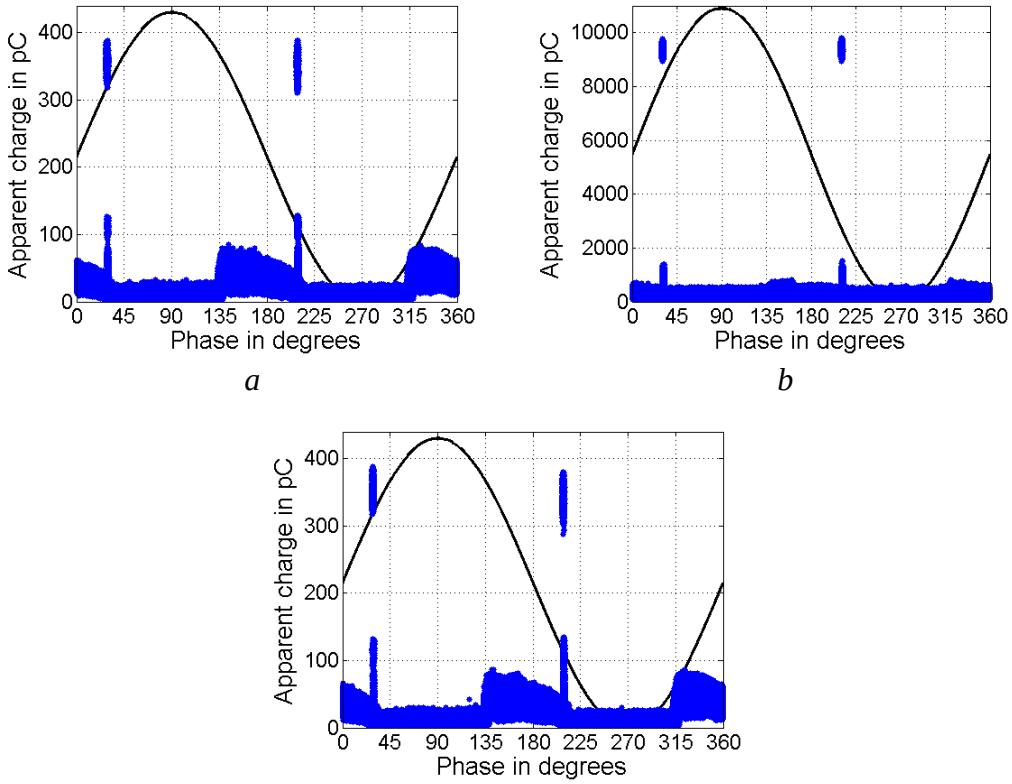


Figure A-5 PRPD patterns of BHV with YHV earthed at a) 3.2 kV, b) 6.4 kV and c) 3.2 kV return for 6.4/0.4 kV DT

LI test results for 6.4/0.4 kV transformer

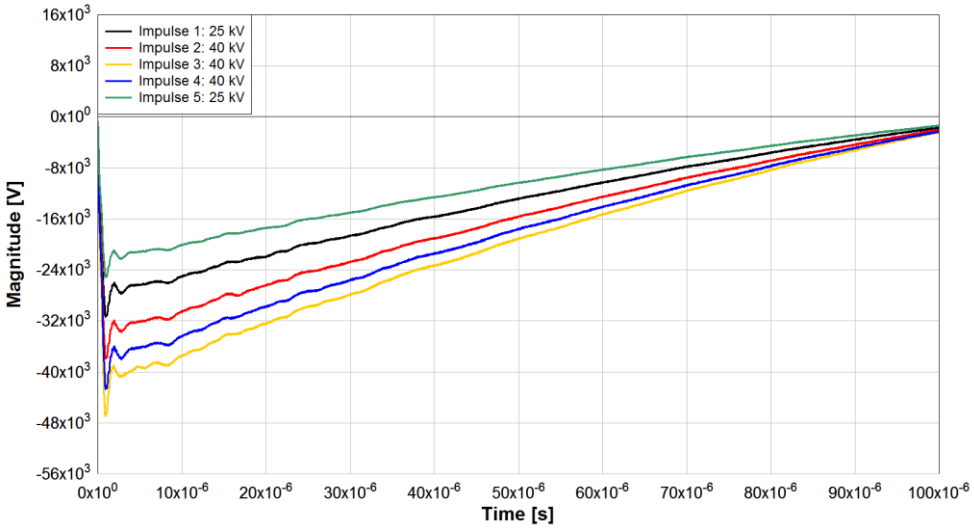


Figure A-6 Impulse voltage waveforms recorded during LI test on R phase for 6.4/0.4 kV DT

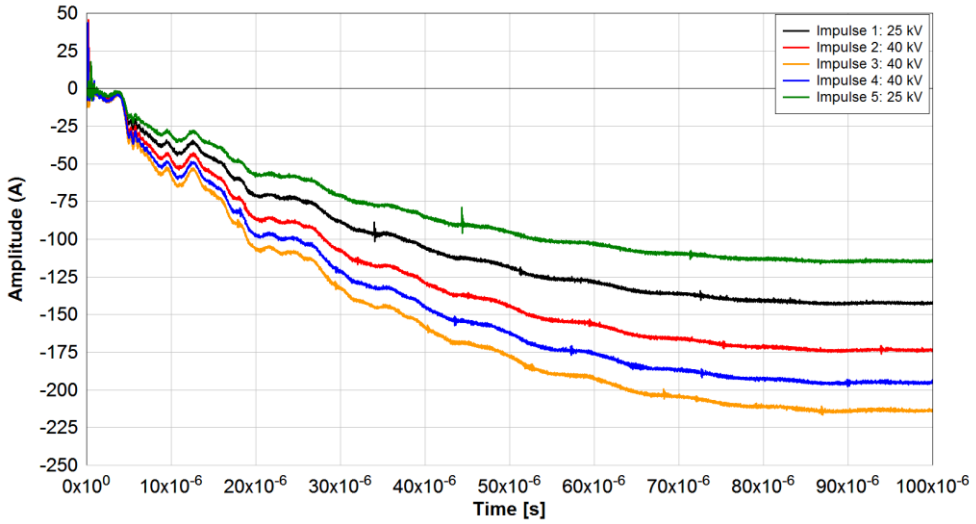


Figure A-7 Current waveforms recorded during LI test on R phase for 6.4/0.4 kV DT

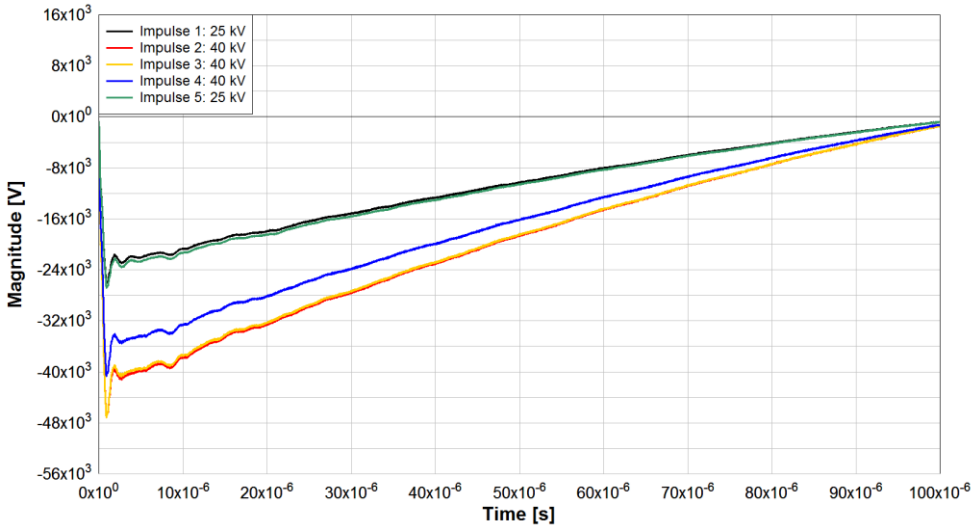


Figure A-8 Impulse voltage waveforms recorded during LI test on Y phase for 6.4/0.4 kV DT

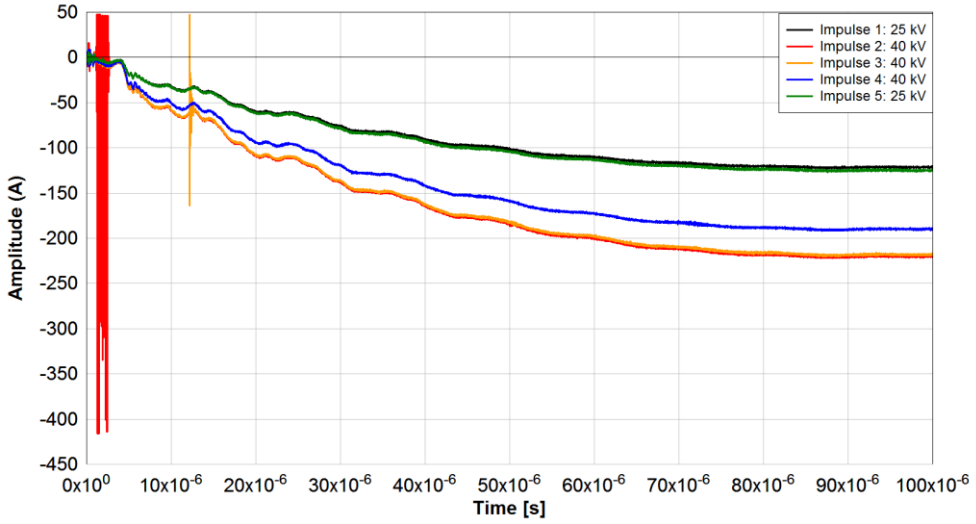


Figure A-9 Current waveforms recorded during LI test on Y phase for 6.4/0.4 kV DT

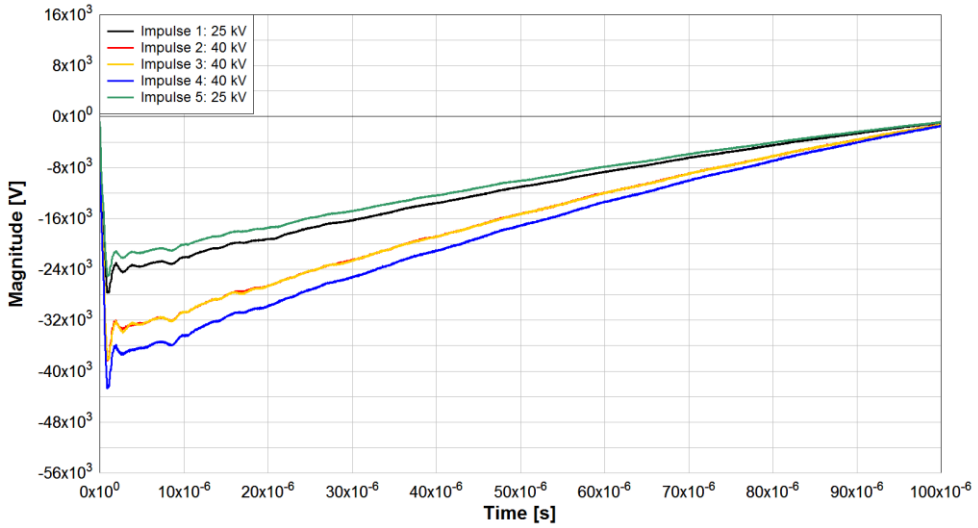


Figure A-10 Impulse voltage waveforms recorded during LI test on B phase for 6.4/0.4 kV DT

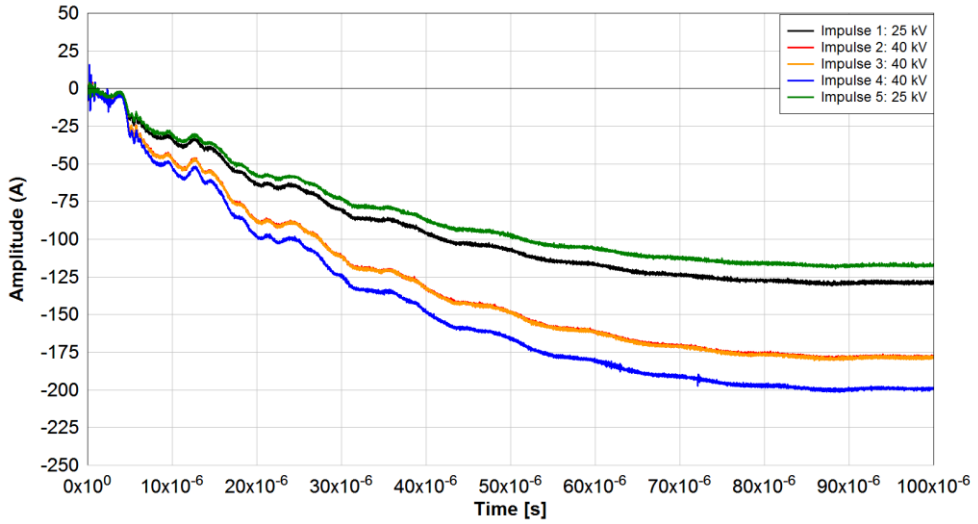


Figure A-11 Current waveforms recorded during LI test on B phase for 6.4/0.4 kV DT

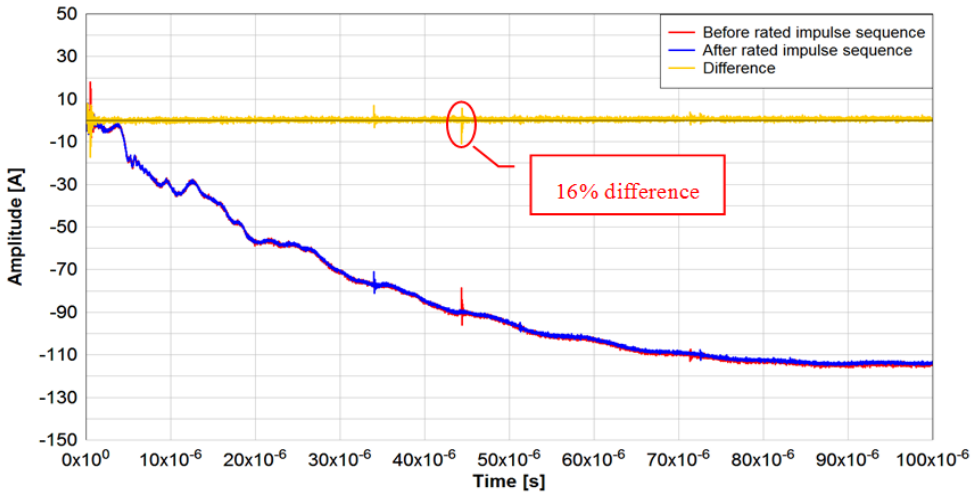


Figure A-12 Comparison of current waveforms of R_{HV} before and after application of rated voltage test sequence for 6.4/0.4 kV DT

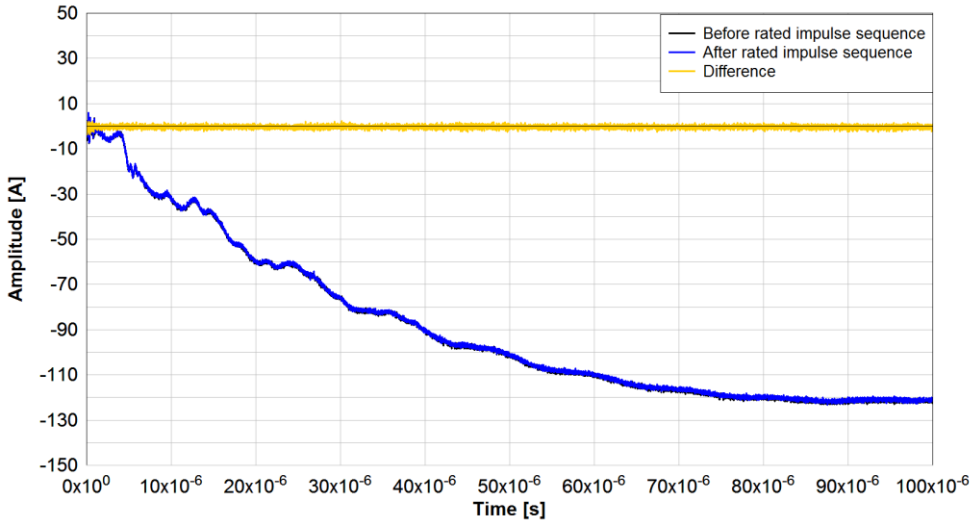


Figure A-13 Comparison of current waveforms of Y_{HV} before and after application of rated voltage test sequence for 6.4/0.4 kV DT

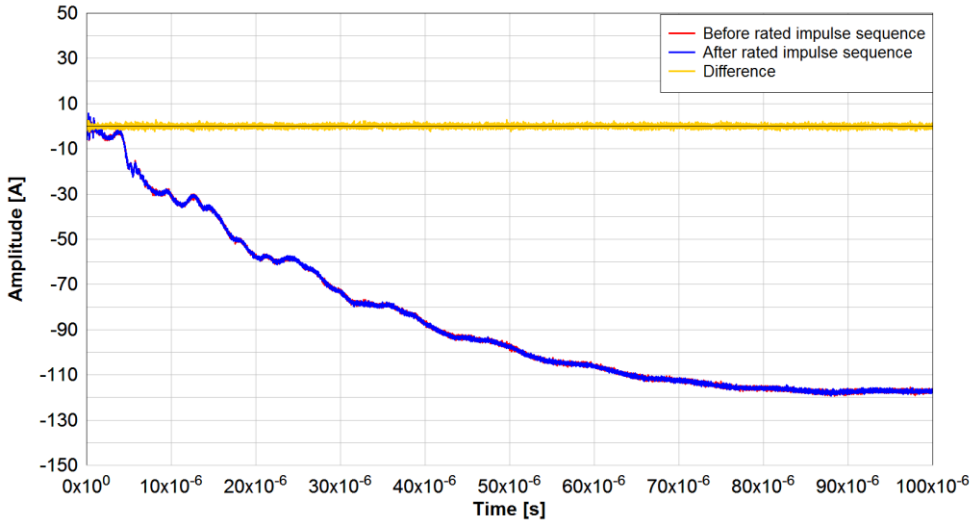


Figure A-14 Comparison of current waveforms of B_{HV} before and after application of rated voltage test sequence for 6.4/0.4 kV DT

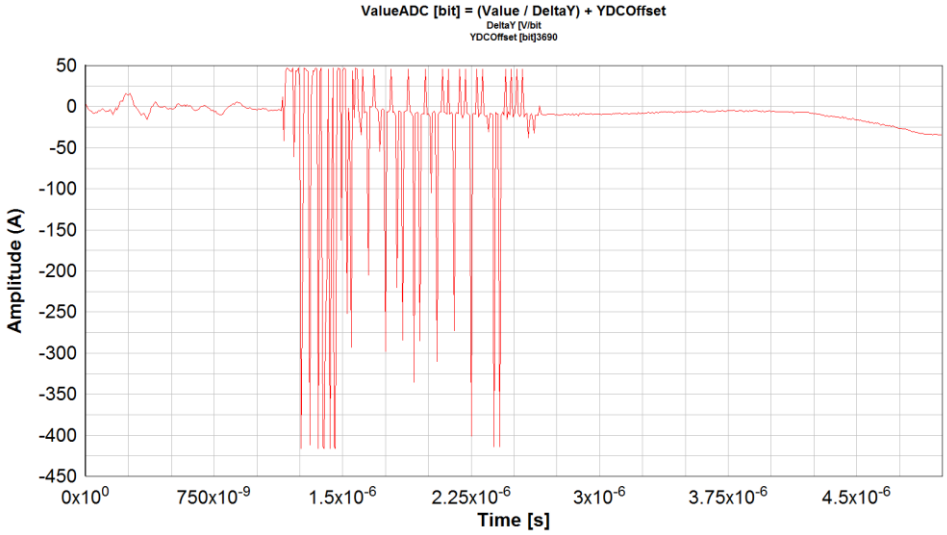


Figure A-15 Expanded plot of the transient peaking during Impulse number 2 in Figure A-9 for 6.4/0.4 kV DT

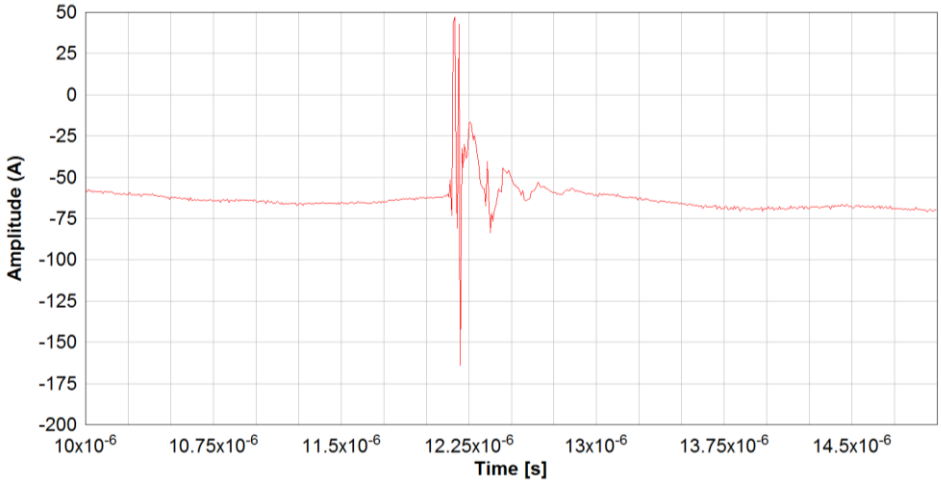


Figure A-16 Expanded plot of the time-shifted and attenuated transient peaking during Impulse number 3 in Figure A-9 for 6.4/0.4 kV DT

Appendix B. Oil Regeneration Experiment on 6.4/0.4 kV Transformer

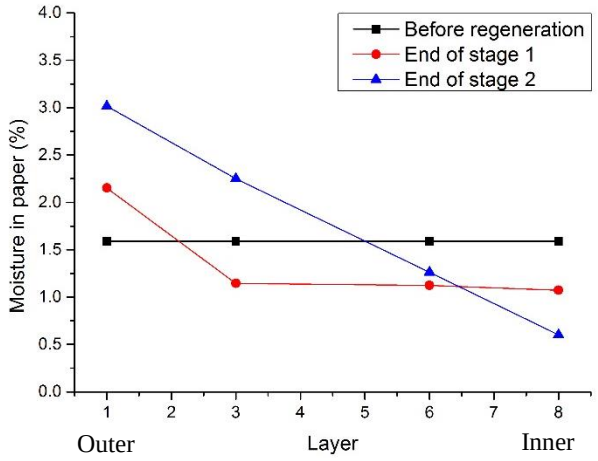


Figure B-1 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2 for TA sample

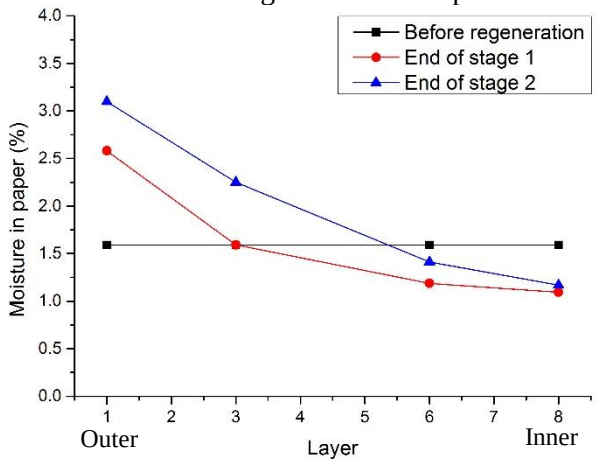


Figure B-2 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2 for BA sample

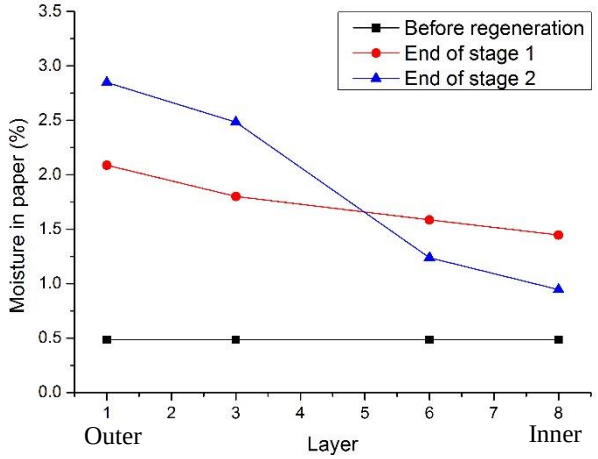


Figure B-3 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2 for TD sample

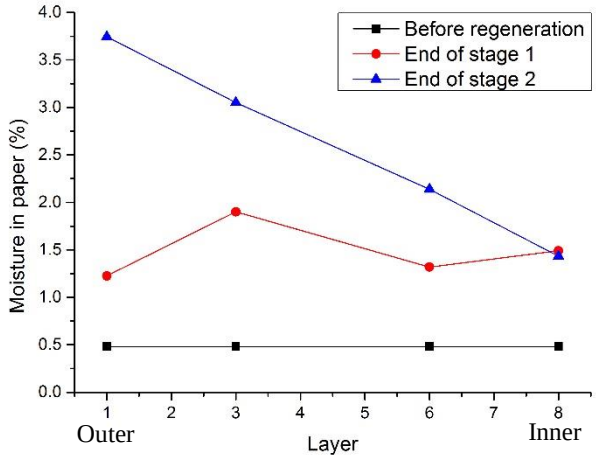


Figure B-4 Profile of moisture in paper before regeneration, at the end of stage 1, and the end of stage 2 for BD sample

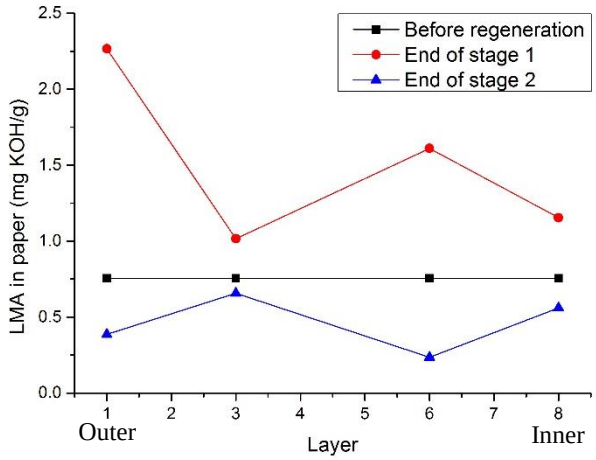


Figure B-5 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2 for TM sample

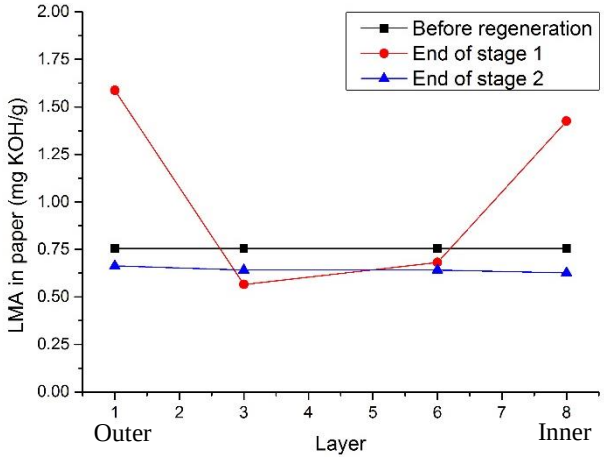


Figure B-6 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2 for BM sample

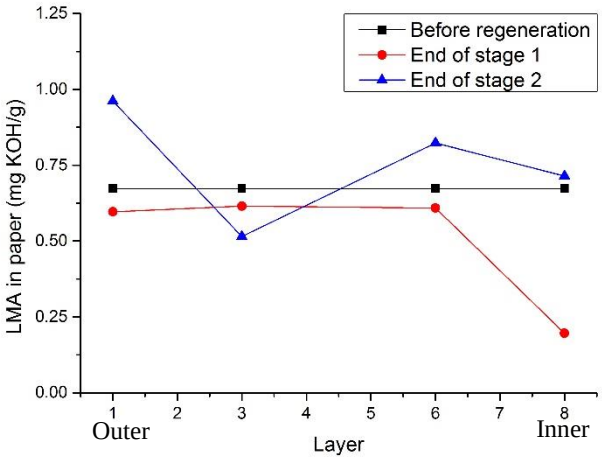


Figure B-7 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2 for TD sample

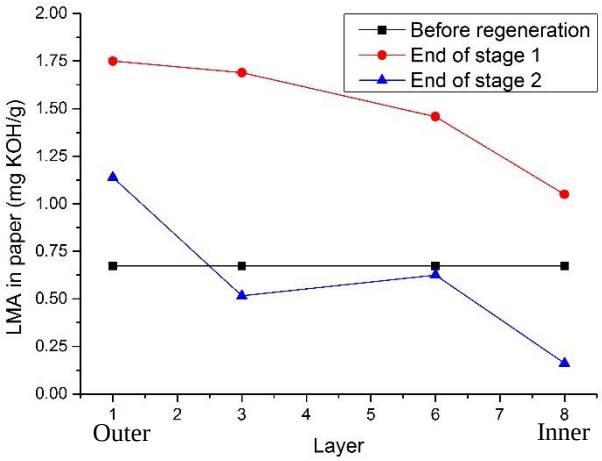


Figure B-8 Profile of LMA in paper before regeneration, at the end of stage 1, and the end of stage 2 for BD sample

Appendix C. List of Publications

1. R. Venkatasubramanian and Q. Liu, “Assessment of Oil Regeneration Techniques for Transformer Health Improvement”, Poster presentation in UHVnet colloquium , Guildford, Surrey, 2014
2. Ramamoorthi Venkatasubramanian, Qiang Liu, and Zhongdong Wang, “Assessment of regenerated oil through accelerated thermal ageing experiments”, International Universities Power Engineering Conference (UPEC), Staffordshire, UK, September 1st - 4th, 2015 (Accepted)
3. Qiang Liu, Ramamoorthi Venkatasubramanian, and Zhongdong Wang, “Effect of oil regeneration on improving paper conditions in a distribution transformer”, IEEE Transactions on Dielectrics and Electrical Insulation (To be submitted)

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