Condition Monitoring of Lubricating Oil used in Marine Vessels

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Award
of Degree of Master of Technology in Marine Technology

by

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ABSTRACT:

The reliability and efficiency of marine propulsion systems heavily depend on the condition of lubricating oil, which serves as both a protective and functional medium for critical engine components. Over time, lubricating oil undergoes degradation due to thermal stress, oxidative reactions, contamination, and prolonged usage. Traditional oil condition monitoring techniques primarily focus on viscosity changes, spectroscopic analysis, and chemical composition assessments. However, in recent years, polarization current analysis has emerged as a promising diagnostic tool for evaluating the dielectric integrity and degradation behaviour of lubricating oils in marine applications. This study explores the application of polarization current measurement as an effective method for monitoring the deterioration of lubricating oil used in marine vessels. The research involves subjecting lubricating oil samples to controlled thermal aging at varying temperatures (40°C, 50°C, 60°C) over extended periods to simulate real operational stress conditions. By applying a 500 V DC voltage using an insulation tester, the resulting polarization current behaviour is recorded and analyse providing valuable insights into molecular breakdown and insulation capacity loss. Experimental findings indicate that as the thermal aging process progresses, the polarization current exhibits increasing magnitudes, signifying a reduction in the resistivity of the lubricating oil. This behaviour aligns with the formation of conductive degradation byproducts such as free radicals, oxidation compounds and polar contaminants, which alter the dielectric properties of the oil. Notably, samples exposed to higher temperatures (50°C and above) demonstrate significant fluctuations in polarization current, suggesting a higher degree of dielectric instability and lubricant deterioration.

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CHAPTER - 1

INTRODUCTION

1.1 Lubricating oil

Lubricating oil is a specialized fluid used to reduce friction between moving parts in mechanical systems. It forms a protective layer that prevents direct metal-to-metal contact, minimizing wear and tear while enhancing efficiency. Viscosity determines the oil's thickness and ability to lubricate under different conditions. Flash point is the temperature at which the oil emits enough vapor to ignite. Pour point is the lowest temperature at which the oil remains fluid. Oxidation stability: resistance to chemical degradation over time. Lubricating oil plays a critical role in marine ships, ensuring smooth operation and longevity of machinery. Here are its major uses: engine lubrication reduces friction between moving parts in main and auxiliary engines. Prevent wear and tear, extending engine life, it helps is cooling by dissipating heat generated during operation. Gear and bearing protection ensure smooth movement of propeller shafts, gears, and bearings. Forms a protective film to prevent metal-to-metal contact. It reduces vibration and noise, improving efficiency. Corrosion prevention protects metal surfaces from seawater exposure. Prevents rust formation in critical components. Enhances durability of ship machinery. Hydraulic systems used in hydraulic machinery like steering gears and winches. Ensures smooth operation of control systems. Prevent fluid degradation under high pressure. Cleaning and sealing help to remove contaminants and debris from engine components. Acts as a sealant to prevent leakage in moving parts. Improves fuel efficiency by maintaining clean surfaces.

1.2 Importance of Lubricating oil in Marine Vessels.

In marine ships, lubricating oil plays a important role ensuring smooth operation and longevity of machinery. Here are its major uses Engine lubrication Reduces friction between moving parts in main and auxiliary engines. Prevents wear and tear, extending engine life. Helps in cooling by dissipating heat generated during operation, ensures smooth movement of propeller shafts, gears, and bearings. Forms a protective film to prevent metal-to-metal contact. Reduces vibration and noise, improving efficiency. Corrosion prevention by protecting metal surfaces from seawater exposure. It prevents against rust formation in critical components to enhances durability of ship machinery. Used in hydraulic machinery like steering gears and winches. Prevents fluid degradation under high pressure. Helps remove contaminants and debris from engine components. Acts as a sealant to prevent leakage in moving parts. Improves fuel efficiency by maintaining clean surfaces.

1.3 Polarization current

Polarization current is a fundamental concept in electromagnetism, describing the movement of bound charges within a dielectric material when subjected to an external electric field. Unlike conduction current, which involves free electrons moving through a conductor, polarization current arises due to the displacement of charges within insulating materials. When an electric field is applied, the molecules or atoms within the dielectric experience dipole alignment, causing a shift in charge distribution. Polarization current analysis helps assess the condition of oil-paper insulation by detecting degradation, moisture ingress, and aging effects. Additionally, in marine engineering, polarization current monitoring is used to evaluate the quality of lubricating oil, ensuring optimal performance of ship propulsion systems. The study of polarization current is essential for improving predictive maintenance strategies, enhancing the reliability of electrical and mechanical systems, and optimizing insulation performance in high-voltage applications.

1.4 Behaviour of Polarization Current:

When a dielectric is placed in an electric field, its internal charges slightly shift and electrons move a bit in the opposite direction of the field, and nuclei slightly in the field's direction. This creates microscopic dipoles throughout the material, a phenomenon called polarization.

If the electric field changes with time, this polarization also changes and that change in polarization over time is what gives rise to polarization current.

Time-Dependent: It only appears when the electric field is varying with time. A static field causes static polarization, with no current.

Direction: The polarization current points in the same direction as the rate of change of the polarization vector ($\partial P/\partial t$).

Magnitude: It's proportional to how fast the polarization changes. A rapid switch in the electric field leads to a strong polarization current.

Displacement Current Tie-In: In Maxwell's equations, the polarization current is part of the displacement current, helping to explain how magnetic fields are produced even in empty space or insulators.

How Polarization Current Reflects Lubricant Health

Fresh Oil:

Exhibits low and rapidly decaying polarization current.

Indicates minimal ionic contamination and strong dielectric integrity.

Additives are intact, and oxidation byproducts are negligible.

Aged or Thermally Degraded Oil:

Shows higher initial polarization current and slower decay.

Caused by increased polar degradation products (e.g., acids, sludge, moisture).

Reflects reduced insulation strength and increased conductivity.

1.5 Difference between Polarization current and conduction current:

Polarization current and conduction current are two distinct phenomena in electromagnetism, each arising from different mechanisms of charge movement. While conduction current involves the flow of free electrons through a conductor, polarization current is associated with the displacement of bound charges within a dielectric material.

Polarization Current occurs due to the displacement of bound charges (dipoles) within a dielectric material when subjected to an external electric field. The molecules or atoms in the dielectric experience dipole alignment, leading to charge redistribution without actual charge flow. Polarization Current found in dielectric materials such as capacitors, insulating oils, and transformer insulation. It plays a crucial role in dielectric spectroscopy and insulation diagnostics. Represents a temporary displacement of charge within a dielectric, which ceases once the dipoles are fully aligned with the applied field. It does not contribute to a continuous flow of charge but affects the dielectric properties of materials.

Conduction Current involves the movement of free electrons or charge carriers through a conductive medium, such as metals or semiconductors. This movement is driven by an applied voltage, resulting in a continuous flow of charge. Conduction Current found in conductive materials like metals, semiconductors, and electrolytes. It is responsible for powering electrical circuits and devices. It Represents a continuous flow of charge carriers, enabling electrical energy transfer in circuits. It is responsible for powering electronic devices and electrical systems.

1.6 Literature Review:

Effect of lubricant ageing on lubricant physical and chemical properties and tribological performance. Part I: effect of lubricant chemistry [1]:

Lubricant ageing can have varying effects on its ability to reduce wear and friction. Generally, as lubricants age, their chemical stability diminishes due to oxidation, additive depletion, and thermal degradation. This typically leads to increased formation of oxidation products, acids, and sludge, which can impair the lubricant's film-forming capacity and tribo-chemical properties. Such degradation can result in poorer lubrication performance and potentially higher wear rates, especially if the lubricant's ability to form protective films is compromised.

However, some studies have observed that aged oils may sometimes form tribo-films with different characteristics, which might offer better wear protection under certain conditions. For example, aged oils can produce films from degradation products such as alkyl sulphides and zinc polyphosphates that might provide more effective wear barriers than fresh oils. Notably, lower wear was observed in some valve-train experiments with aged oils, possibly due to these secondary film formations, although the underlying mechanisms remain unclear.

Overall, the impact of lubricant ageing on friction and wear is complex and depends on factors like the extent of chemical degradation, the presence of specific degradation products, and the operational environment. While ageing generally hampers lubricant performance, certain chemical changes might unexpectedly improve wear protection under specific conditions.

Effect of Ageing on Lubricants Physical and Chemical Properties and Tribological Performance: Part II – Effect of Water Contamination on Lubricant [2]:

This study investigates how water contamination affects the ageing behaviour of different lubricants and their tribological performance, expanding on findings from Part I. It focuses on how water interacts with various base oils (PAO, ester, mineral) and additives (ZDDP, phosphoric ester, corrosion inhibitors). Experimental Framework is the Lubricants were contaminated with 1 wt% distilled water and aged for 6 weeks at 80 °C using steel rollers. Evaluations included viscosity (ASTM D7042), TAN (ASTM D664), FTIR analysis, tribological testing (ball-on-disc), and surface chemistry via XPS. Physical and chemical Changes such as Water Concentration is decreased over time, attributed to evaporation and hydrolysis. In viscosity there is Largely unchanged across all lubricant samples. Total Acid Number (TAN) Ester-based lubricants showed significant TAN increases means poor hydrolytic stability. PAO and MO lubricants saw TAN decrease likely due to lower acidity of hydrolysis by-products compared to original additives. Tribological Performance Friction: Barely affected by water ageing. Wear is Increased with water contamination due to degraded ZDDP and reduced surface protection. ZDDP remained more effective in ester-based oils than PAO-based ones. Tribo-film Chemistry (XPS) shows that Water led to a reduction in surface oxide content, potentially reducing wear resistance. Degradation of ZDDP observed via FTIR water accelerates breakdown of anti-wear additives. It concluded that Water contamination significantly accelerates the chemical degradation of lubricants, especially those with ester bases. Although viscosity remains stable, elevated TAN and reduced effectiveness of anti-wear additives like ZDDP lead to higher wear rates. The study highlights the crucial role of tribo-chemical interactions, not just bulk properties, in determining lubricant performance under humid conditions a key concern in marine, wind energy, and paper industry applications.

A Quantitative and Qualitative Analysis of the Lubricity of Used Lubricating Oil Diluted with Diesel Oil [3]:

The researchers investigated how diesel oil (DO) dilution affects the *lubricity* of both fresh lubricating oil (FLO) and used lubricating oil (ULO). The aim was to determine whether used oil diluted with diesel behaves similarly to fresh oil in terms of wear characteristics, friction, and oil film thickness. Lubricity initially improves at low DO concentrations (1–2% m/m) due to better adhesion from diesel components. Beyond 2% DO, lubricity declines, wear increases, and oil film weakens, potentially risking engine damage. Used oil offers slightly better lubricity than fresh oil at the same diesel concentrations—attributed to aging byproducts like resins and acids. Linear trends observed changes in WS1.4, μ (Coefficient of friction) and r (Relative reduction in oil film thickness) generally followed linear relationships with diesel concentration, although more complex models could improve accuracy. FLO mixtures showed *oval* wear scars; ULO samples had *rounder, more uniform* scars. Grooving was more common in ULO tests, likely due to the presence of solid contaminants. Increased diesel content led to deeper wear scars and more pronounced abrasion. In Conclusion Used oil diluted with diesel follows *similar degradation trends* to fresh oil, supporting the hypothesis. The findings help establish baselines for assessing engine oil condition in marine power systems, especially regarding fuel contamination.

Thermal Degradation Process of Synthetic Lubricating Oils: Part I – Spectroscopic Study. [4]:

The study investigates how synthetic lubricating oils degrade thermally by using spectroscopic techniques to analyse oxidation byproducts formed at different temperatures and durations. Lubricant: Brazilian commercial automotive synthetic oil (API SJ, SAE 20W-50) with additives. Heated at 150°C–210°C in air for up to 48 hours. Analysed by Used IR spectroscopy, ^1H and ^13C NMR, GC/MS, and XRF for sulfur content. Oxidation is the primary degradation mechanism. Sulphur content decreased significantly after degradation (from 0.649% to 0.351%), possibly due to SO_2 formation. IR spectra showed changes in functional groups like C=O, O-H, and C-O, confirming oxidation. NMR spectra revealed new peaks indicating formation of ketones, carboxylic acids, and unsaturated compounds. GC/MS showed minor shifts in hydrocarbon chain composition but no major structural breakdown—long-chain alkanes (C21–C25) remained dominant. Oxidation during high-temperature exposure causes chemical transformations in synthetic lubricants, impacting their performance. This highlights the importance of thermal stability in lubricant formulation and motivates further research into degradation-resistant additives.

Arrhenius Equation for Calculating Viscosity in Assessing the Dilution Level of Lubricating Oil with Diesel Oil—A Case Study of SAE 30 and SAE 40 Grade Marine Lubricating Oils [5]:

The article explores a practical application of the Arrhenius equation to assess the dilution level of marine lubricating oils (SAE 30 and SAE 40) with diesel oil, a scenario commonly encountered in marine diesel engine operation. Diesel fuel contamination in lubricating oil degrades engine performance, increases wear, and poses safety risks (e.g., crankcase explosions). The Objective is to use the Arrhenius viscosity mixing model to estimate the viscosity of a known mix of diesel and lubricating oil. Diesel concentration from a measured viscosity value. The Method of Mixtures were prepared with diesel concentrations from 0% to 100% and tested at various temperatures (40–100°C). Model Adaptation: Instead of mole fractions, mass fractions were used to simplify the formula for practical use with similar-density oils. The Arrhenius model reasonably estimates viscosity and diesel concentration, especially for <5% diesel, which is common in practice. Errors increase at lower temperatures and higher diesel concentrations but remain acceptable for operational monitoring. Model accuracy improves with increasing temperature and similarity in oil properties. The Arrhenius equation in the context of viscosity modelling is a beautifully simple yet powerful tool derived from physical chemistry. Originally, it was used to describe how reaction rates vary with temperature, but in this study, it’s cleverly adapted to describe how the viscosity of a mixture depends on the viscosities and proportions of its components. In mixtures of similar organic liquids (like mineral oils), molecular interactions are fairly predictable, so viscosity trends behave quasi-logarithmically—not linearly. This is especially useful when the two liquids are chemically similar (e.g., hydrocarbons), Viscosity contrast isn't extreme, Characterization and Differentiation of Chemical Fingerprints of Virgin and Used Lubricating Oils for Identification of Contamination or Adulteration Sources.[6]

The researchers developed a multi-criteria fingerprinting approach using advanced chromatographic and spectrometric tools to distinguish virgin lube oils from used and adulterated ones. They analyzed virgin oil (20W-50), used oils (from gasoline and diesel engines), waste oil from mixed sources, diesel, and a biodiesel blend. Chemical Separation & detection is used for silica gel columns for sample cleanup and separation. Performed gas chromatography with flame-ionization detection (GC-FID) to profile total petroleum hydrocarbons (TPH). Used gas chromatography-mass spectrometry (GC-MS) in selected ion monitoring (SIM) mode to identify the Polycyclic aromatic hydrocarbons (PAHs) such as Biomarkers (e.g. hopanes, steranes), Fatty acid methyl esters (FAMEs), Small, stable hydrocarbons like adamantanes and diamantanes. Diagnostic Ratios is utilized by ratios of key hydrocarbon components and biomarker distributions to determine oil origin and contamination patterns. Virgin vs. Used Oils: Virgin oils were chemically cleaner with less aromatic and resolved components. Used oils showed traces of unburned fuels, combustion products, and contaminants. Increased concentrations of PAHs and presence of diesel-range compounds, light biomarkers, and FAMEs in used oils indicated mixing with diesel and biodiesel—pointing to either engine contamination or intentional adulteration. Peaks of C16:0 and C18:1 FAMEs signified palm-based biodiesel residues, suggesting fuel-origin contamination. The pattern and abundance of terpanes, steranes were crucial for source differentiation—allowing the team to distinguish oil types and sources of mixing.

Review of condition monitoring and fault diagnosis (CMFD) for marine power systems [7]:

The paper reviews the evolution of Condition Monitoring and Fault Diagnosis (CMFD) techniques for marine power systems, which are essential for ensuring maritime safety, especially as ships become smarter and more eco-friendly. The development is divided into three generations. First Generation is Based on field-testing techniques (e.g., vibration, performance parameters, and oil analysis). Second Generation is shifted to online condition monitoring and remote diagnosis, integrating sensors, networks, and computer systems. Third Generation Utilizes intelligent fault diagnosis, including AI, machine learning, and expert systems for real-time, predictive diagnostics. They supplement this review with real-world applications on various ships—like dredgers, salvage ships, container vessels, and a solar photovoltaic Ro-Ro ship—and outline future research directions toward greener and smarter shipping supported by intelligent CMFD platforms. The paper breaks down methods across the three CMFD generations. Signal Acquisition Techniques are used to collect diagnostic data. Performance parameters like Temperature, pressure, fuel consumption, etc., used for simulating engine faults. Offline and portable methods measuring viscosity, acid number, wear particles of Oil Monitoring. Vibration Monitoring detects unbalance, wear, or misalignment using displacement, velocity, and acceleration signals. Feature Extraction Techniques is to identify useful fault characteristics. From Oil Particles are uses for image processing, morphology, fractals, and texture analysis. From Vibration Signals Time Domain such as RMS, kurtosis, peak value, etc. and Frequency Domain such as Spectral analysis. Time-Frequency Domain in this Wavelet transforms, EMD, Hilbert spectrum is suitable for non-stationary signals. Online and Remote Monitoring, Online systems monitor parameters like vibration and oil in real time. Remote diagnosis leverages satellite/Internet tech to communicate data between ship and shore. Intelligent Diagnosis is the third generation focuses on smart, data-driven approaches the Quantitative Models which Use physical/mathematical models (e.g., Kalman filters) for predictive diagnostics. Statistical and Signal-Based Techniques: PCA, ICA, entropy methods, wavelet and spectral analysis. Machine Learning ANNs, SVMs, Deep Learning (CNNs, LSTMs) for fault classification and prediction. Fusion methods using Dempster–Shafer and belief rule bases for multi-source sensor integration.

A lubricant condition monitoring approach for maintenance decision support - a data exploratory case study. [8]:

Lubricant condition monitoring especially UOA is vital in Condition-Based Maintenance (CBM) for detecting both oil degradation and equipment wear. Traditional UOA programs often focus on individual parameter thresholds but rarely leverage correlations between parameters or link them with actual failure events. This study addresses those gaps by integrating statistical methods with maintenance records to detect failure patterns and enhance decision support.

Methodology:

Data Collection & Preprocessing: Used oil test results (75 samples) and failure event logs (86 events) from one engine in a thermal power plant were collected. Preprocessing involved cleaning, integrating, and validating the data, often with input from the maintenance team.

Data Standardization: Failure data were structured according to the ISO 14224:2016 standard for uniformity and effective subsystem classification (e.g., Cylinder, Turbocharger).

Normality Testing: Shapiro-Wilk tests were used to evaluate whether parameters followed a normal distribution. Only about 25% were normally distributed, guiding the choice of correlation method.

Correlation Analysis: The Spearman rank correlation was employed due to non-normality of data. A correlogram revealed significant associations—e.g., flash point strongly correlating with water content, and viscosity at 40°C correlating with wear metals like iron and nickel.

Trend Analysis: Time-series plots of parameters (e.g., viscosity, zinc, tin, iron) highlighted deviations from industry thresholds, flagging potential degradation or contamination events.

Interpretation & Decision Support: Correlated parameter anomalies were cross-referenced with actual failure records. For instance:

High water content and flash point correlated with cylinder head gasket failures linked to water leaks. High viscosity and wear metals (iron/nickel) aligned with fuel injector failures, suggesting fuel dilution. This hybrid approach allowed the researchers to detect early signs of mechanical failures and propose predictive maintenance actions, ultimately improving equipment reliability and operational efficiency.

Understanding carbonaceous deposit formation resulting from engine oil degradation. [9]:

This study explores how carbonaceous deposits form in the first piston ring grooves of direct injection diesel engines due to engine oil degradation. The primary culprit is the thermal and oxidative breakdown of engine lubricants during engine operation, especially under high-temperature and high-wear conditions. The paper identifies two main types of deposits. Oily deposits are High in volatile organics, appear under milder conditions. Dry deposits are Depleted in volatile content, resulting from more severe test conditions like prolonged engine run time or higher oil sump temperatures. These deposits mainly form from oxidation, polymerization, and interaction with soot and metallic wear particles, reducing engine performance and durability. In this the researchers used a two-part experimental approach. First is Real-Engine Tests in this Engines were operated under different test severities: endurance vs. Real driving, various oil sump temperatures (up to 145°C), and durations (up to 400 hours).

Lubricant used is SAE 5W-30 with low sulfur diesel fuel (and added cerium oxide to track fuel's role in deposit formation). Deposits were collected from pistons after tests, especially from the first ring grooves. Analytical techniques used are SEM/EDX is a study of morphology and elemental composition. TGA (Thermogravimetric Analysis) for check the thermal stability and volatility of deposit constituents. FT-IR identifies the oxidation products (carbonyls, aromatics). Pyrolysis-GC/MS Identifies volatile and polymerized compounds, especially aromatics like benzene and phenanthrene. Simulated Thermo-Oxidative Degradation is Conducted in a tubular furnace to mimic engine conditions under Temperature of 150°C, 225°C and 350°C with respect to Time of 2–10 hours. It is found easy the carbonyl content and reduced antioxidant effectiveness. Deposits from higher temperatures visually and chemically resembled those from real engine tests. Temperature is the most influential factor in deposit formation, followed by test duration and presence of metallic particles. The oxidation of oil not only forms harmful varnishes and sludges but also traps wear metals and soot forming stubborn carbonaceous buildups.

Study of the Relationship between the Level of Lubricating Oil Contamination with Distillation Fuel and the Risk of Explosion in the Crankcase of a Marine Trunk Type Engine [10]

The study investigates how diesel fuel contamination in lubricating oil influences the risk of crankcase explosions in marine trunk piston engines. The central hypothesis is that even though fuel contamination might seem to primarily affect the oil's ignition properties (like lowering the flash point), it also degrades its lubrication performance. In other words, diesel fuel in the oil can both change how easily the oil vaporizes (affecting ignition) and alter its viscosity and wear characteristics (affecting friction and heat generation). Together, these factors can create hot spots or conditions that favour an explosion in the engine's crankcase. The experiment focused on two widely used marine lubricating oil types—SAE 30 and SAE 40. These oils were intentionally blended with diesel fuel at various weight percentages (0%, 1%, 2%, 5%, 10%, 20%, 50%, and 100%) to simulate different levels of contamination. The study then measured three key groups of properties:

Rheological Properties:

Density and Viscosity: Using instruments such as the Anton Paar DMA 4500 for density and a Cannon-Fenske viscometer for kinematic viscosity, the study examined how the oil's density and viscosity changed with temperature (from 15 °C to 100 °C) and diesel content.

Viscosity Index (VI): From the measured viscosities at different temperatures, the viscosity index was calculated. The VI indicates how sensitive the oil's viscosity is to temperature changes. Increasing diesel content was found to modify the viscosity behaviour, which is critical for both lubrication performance and the formation of oil mist.

Lubrication Properties:

Lubricity: The researchers employed a high-frequency reciprocating rig (HFFR) tribometer. This device measured the wear scar diameter (WSD) on a test ball, providing a quantitative assessment of the oil's lubricity.

Friction and Oil Film Resistance: Alongside wear measures, the friction coefficient and the percentage loss of oil film resistance were recorded. These metrics indicate how the oil performs as a protective film between moving engine parts—a degradation here can lead to increased heat and, eventually, the formation of hot spots.

Ignition Properties:

Flash Point Measurement: A Pensky-Martens apparatus was used to determine the flash point of the oil and oil–diesel blends. Because diesel has a lower flash point than lubricating oil, even a modest contamination (for example, around 5% by mass) can notably reduce the oil's flash point, making it more susceptible to ignition under high-temperature conditions.

Calculated Ignition Indices: Additionally, ignition quality was characterized by calculating indices such as the derived cetane number (DCN), calculated cetane index (CCI), calculated ignition index (CII), and the carbon aromaticity index (CCAI). Although these indices are more commonly applied to fuels, they provided insight into how the ignition delay and autoignition properties change as diesel content increases.

Strategic oil analysis. Estimating remaining lubricant life. [11]:

This article lays the groundwork for understanding lubricant degradation, especially due to oxidation, and how it can be predicted and managed through oil analysis. The key message is: lubricant life can be extended—and machine reliability preserved—by understanding the chemistry of oil degradation and proactively measuring it. Oxidation is the dominant mechanism for oil degradation and involves free radical chain reactions that create harmful byproducts like acids, sludge, and varnish. The base oil type and antioxidant package are the two most critical factors determining oxidative stability. Monitoring antioxidant depletion and byproduct formation helps estimate remaining lubricant life and informs oil change schedules.

Lubricant oxidation unfolds in three stages. First is initiation where Free radicals are generated by heat, oxygen, wear metals, UV light, and even flow electrification. These radicals are highly reactive. Propagation in this peroxide radicals continue the chain reaction by reacting with base oil molecules, especially under heat or metal catalysis. Termination is antioxidants (additives like phenols and amines) neutralize radicals to halt the reaction. Once consumed, the oil rapidly degrades.

Methods for measuring lubricant degradation measuring the *cause* (additive depletion FTIR (Fourier transform infrared spectroscopy) detects molecular fingerprints to track oxidation, nitration, sulfation, and additive degradation. LSY (linear sweep voltammetry) measures remaining antioxidants (e.g., phenols and amines) via an electrochemical response quantified remaining useful life. Measuring the effect

Total Acid Number: Measures acidity increase, though it only detects later-stage degradation.

Ultra-Centrifuge: Separates sludge and sediment to visually assess the quantity of insoluble.

Membrane Patch Colorimetry: Filters and measures varnish-forming insoluble with a colour scale (AE values); values >40 are concerning.

Benefits of lubricant oil analysis for maintenance decision support: a case study. [12]

The paper describes the application of oil condition monitoring to assist in determining the appropriate interval for the replacement of hydraulic oil. Four basic oil condition parameters were observed, over a period of 20 months. In the case of asphalt paving machine, sample analysis and analysis of the trends of change in each of the parameters indicate that oil filling can continue to be used in exploitation for a quite some time. Also, this means that oil condition parameters should be monitored, until the time comes to change the oil. In case when managers acquire adequate information on oil’s condition, it is not obligatory to strictly adhere to the manufacturer's recommendation. This eliminates the cost of premature oil replacement, unnecessary service engagement, and other costs associated with the removal of waste oil and filters. Maintenance managers are more independent in reaching the decisions if they obtain qualitative information about the machines condition and state. In addition to determining the most appropriate interval of oil replacement, using other condition monitoring techniques, early failures can be identified, timely prepare the material and required workforce and more precisely determine the optimal replacement intervals for the component which has failed.

Investigation of used engine oil lubricating performance through oil analysis and friction and wear measurements. [13]

The researchers aimed to analyze the degradation of engine oil over its service life and evaluate how its lubricating performance (friction and wear) changes with time. They focused on identifying key indicators of oil condition (like TAN,TBNS, boron), linking those to actual friction and wear behaviour and developing predictive models using chemical properties. In the test setup identical diesel engines (light-duty, direct injection, turbocharged) were used. Each engine underwent a different test cycle to simulate varying conditions. Simulated real-life driving (mixed load & speed), focused on stressing the EGR system pushed engine to its limits (high speed & full throttle). Lubricant used is commercial sae 0w-30 fully synthetic oil used. oil change interval is after every 250 hours. oil samples collected every 50 hours from each engine. Total of 43 samples were analysed. Each sample underwent lab testing for various properties:

Physical	Kinematic Viscosity at 40°C and 100°C
Chemical	Total Acid Number (TAN), Total Base Number (TBN)
Contaminants	Soot (%), Na, Si, Al, Cr, Cu
Wear Metals	Fe (iron), and additives like Zn, Ca, Mg, P, B (boron)
Analytical Methods	ASTM and DIN standards

To test the lubricating performance of aged oil. They used a high-frequency reciprocating rig a tribometer setup that mimics sliding contact conditions. Ball-on-disc setup is steel on steel pair. Testing parameters followed by ISO 19291:2016, including load 300n, frequency 50 hz, and duration of 7230 s, temperature at 50°c and outputs measured such as coefficient of friction (COF) and Average wear scar diameter on the steel ball (via optical microscopy).

Engineering Tests for Marine Turbine Lubricating Oils [14].

The paper "Engineering Tests for Marine Turbine Lubricating Oils" offers a comprehensive examination of the performance and risks associated with lubricating oils used in geared marine steam turbines. It is structured in two parts. The first part focuses on evaluating the anti-scuffing properties of oils using a perpendicular-axes disc machine developed by the British Ship Research Association. Through controlled tests on different gear steel combinations, it assesses how E.P. (extreme pressure) additives influence gear protection under various sliding conditions. The second part addresses a specific failure mode machining-type damage in turbine thrust blocks, especially in high-pressure turbines. Using a custom disc rig and full-scale test setups, the authors investigate how certain oil and steel combinations can lead to catastrophic wear known as “wire wool” failures, sometimes without warning signs. They found that used oils often showed degraded performance compared to fresh samples, especially those with chlorinated E.P. additives. The study concludes that oil-steel compatibility is critical and recommends avoiding certain E.P. oils unless essential, highlighting the need for cleaner systems, better filtration, and fundamental research into the chemistry of lubricant degradation. It describes two core experimental setups to evaluate marine turbine lubricating oils. The first involves a perpendicular-axes disc machine designed to assess the anti-scuffing properties of oils. This test rig uses two steel discs one rotating and the other loaded against it—to simulate the sliding and rolling contact between gear teeth under controlled conditions. By varying speed, load, and slide/roll ratio, the machine measures the point at which scuffing failure occurs, indicated by changes in torque, noise, and sometimes even sparks. Oils are then ranked based on their ability to delay or prevent scuffing under these conditions. The second part focuses on machining-type failures in turbine thrust blocks, notably in high-pressure turbines. Researchers developed a disc-type thrust test rig with real thrust pad and collar materials, which were embedded with hard particles like chilled iron shot to simulate contamination. Under set loads and speeds, they observed whether the oil-steel combination would lead to wire wool formation and scabbed pads, hallmarks of a catastrophic failure. Interestingly, the tests revealed that certain oils, especially those with chlorinated extreme pressure (E.P.) additives, were more prone to induce such failures especially after being used at sea even when oil analyses showed no alarming changes.

A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant. [15]

The paper offers an in-depth review of various cooling and lubrication strategies used in metal machining, with a strong emphasis on the potential of minimum quantity lubrication (MQL) using vegetable oil-based lubricants. The authors critique traditional flood cooling for its high environmental and health risks due to mineral-based cutting fluids, and highlight alternative methods like high pressure coolant, cryogenic cooling, solid lubricants, gas/vapor coolants, and particularly MQL. They advocate for MQL as a cost-effective, eco-friendly solution that performs well across drilling, turning, milling, and grinding—especially when paired with biodegradable vegetable oils. O support this, the paper synthesizes numerous experimental studies across machining operations. For instance, in turning AISI 9310 steel, MQL with palm oil reduced tool wear and improved surface finish significantly compared to dry and flood cooling. In drilling titanium alloys, vegetable-based MQL reduced thrust force and extended tool life. Experiments in milling and grinding similarly showed lower friction, better dimensional accuracy, and reduced heat when using MQL especially at higher speeds. Various setups included comparisons of lubricants, flow rates, air pressures, and tool materials, demonstrating MQL's versatility. Importantly, the studies also reveal that vegetable oils outperform mineral oils in lubrication performance and reduce machining costs while being safer for operators and the environment.

Chemistry and Technology of Lubricants. [16]

The study provides an extensive overview of oil analysis and condition monitoring, emphasizing their role in maintaining machinery reliability and minimizing maintenance costs. It distinguishes between performance testing and condition monitoring—while the former evaluates lubricant suitability, the latter detects signs of oil failure modes like contamination (water, fuel, glycol, dirt, soot, metals) and degradation (oxidation, nitration, sulphation, additive depletion). It details various test methods including FT-IR spectroscopy, particle counting, elemental analysis (AE, ICP, XRF), viscosity testing, and supplemental techniques like gas chromatography and Karl Fischer titration. The document stresses the significance of managing condition data through automated expert systems that apply statistical process control, trend analysis, and diagnostic algorithms to determine maintenance needs. Ultimately, it underscores the importance of understanding machinery failure modes, selecting appropriate monitoring techniques, and interpreting data effectively to support proactive, cost-efficient maintenance strategies. The paper outlines several advanced oil analysis and condition monitoring techniques each tailored to detect specific failure modes and maintain machinery health. Infrared (IR) spectroscopy, particularly Fourier Transform Infrared (FT-IR), is widely used to monitor oil degradation, contamination (like water, fuel, soot, and glycol), and additive depletion by measuring molecular absorption patterns. Electronic particle counting (EPC) is employed to determine fluid cleanliness, relying on light extinction principles and ISO 4406 codes to quantify solid contaminants like dirt and wear particles. Elemental analysis further supports diagnostics through methods like Rotating Disk Electrode (RDE) and Inductively Coupled Plasma (ICP) spectroscopy, which respectively detect larger and smaller metal particles, while X-Ray Fluorescence (XRF) identifies metal concentrations using characteristic X-ray emissions. Viscosity testing, often via kinematic viscosity measurements, flags abnormalities such as dilution or thickening caused by contamination or degradation. Supplementary tests like Karl Fischer titration accurately detect water content, gas chromatography identifies trace levels of fuel or glycol, and the RULER test evaluates antioxidant health. Portable tools like the Fuel Sniffer use vapor analysis for field diagnostics. Combined, these methods enable robust, data-driven oil condition assessment programs that support predictive maintenance—aligning perfectly with your passion for real-time monitoring and Condition-Based Maintenance strategies.

1.7 Objective of Research

Condition monitoring of lubricating oil in marine vessels is a critical practice aimed at ensuring the efficiency, reliability, and longevity of ship machinery. The primary objectives include preventing machinery failure lubricating oil plays a vital role in reducing friction and wear in marine engines, gearboxes, and other mechanical components. Regular monitoring helps detect contaminants, degradation, or abnormal wear patterns, preventing unexpected breakdowns. Optimising maintenance schedules instead of relying on fixed maintenance intervals, condition monitoring allows ship operators to adopt a predictive maintenance approach. By analysing oil quality, they can determine the right time for oil replacement or machinery servicing, reducing unnecessary downtime. Enhancing fuel efficiency poor-quality lubricating oil can lead to increased friction and energy loss, negatively impacting fuel consumption. Monitoring oil condition ensures optimal lubrication, contributing to better fuel efficiency and lower operational costs. Extending equipment lifespan contaminants such as water, metal particles, and oxidation byproducts can accelerate wear and corrosion in marine engines. By identifying these issues early, contributing to better fuel efficiency and lower operational costs. Extending equipment lifespan contaminants such as water, metal particles, and oxidation byproducts can accelerate wear and corrosion in marine engines. By identifying these issues early, corrective actions can be taken to prolong the lifespan of expensive ship machinery. Reducing environmental impact proper oil monitoring minimizes the risk of oil leaks and spills, which can harm marine ecosystems. Additionally, extending oil life reduces waste generation, supporting sustainable maritime operations. Ensuring compliance with regulations many maritime authorities and classification societies require regular oil condition monitoring to ensure vessels meet safety and environmental standards. Compliance with these regulations helps avoid penalties and ensures smooth operations. Monitoring the health of lubricants through polarization current analysis offers a sensitive method for detecting degradation, particularly in systems where insulating performance is critical. When a direct voltage is applied across a lubricant sample, the resulting polarization current reflects the alignment of dipolar molecules and migration of ionic species. In fresh oil, the polarization current is low and decays rapidly, indicating good dielectric properties and minimal contamination. However, in aged or thermally degraded oil, the current is initially higher and decays more slowly due to the presence of polar oxidation byproducts, acids, moisture, and sludge. This shift indicates a decline in dielectric strength, increased conductivity, and reduced insulation effectiveness.

CHAPTER - 2

Experimental Investigations

2.1 METHODOLOGY

The experiment investigates the thermal degradation of lubricating oil subjected to controlled heating over a period of four days using a microwave system. The oil samples were exposed to incremental temperature levels of 40°C, 50°C and 60°C to assess the effects of prolonged thermal stress on their electrical and dielectric properties.

Following 7 days heating, a 25 mL portion of the lubricating oil was transferred to a glass beaker, subsequently placed within a steel container for controlled testing. Using an Insulation Tester, a 500 V DC potential was applied to measure the polarization current behaviour, a key indicator of dielectric integrity and insulation resistance.

2.2 Experimental Setup

Firstly, we take a lubricating oil called by Machine oil which is commonly used in electrical and mechanical instruments for enhancing performance. We take a 1 Liter of machine oil in steel container shown in (figure- 1) and placed it in hot air oven"ILB-101 HOT AIR OVEN" shown in (figure- 2) for 7 days at temperature of 40 degree Celsius to give external heat for its thermal aging. After 7 days, we take 25 ml of machine oil for sample test and put the rest container of machine oil again in Hot air oven for thermal aging at temperature set at 50 degrees Celsius. Taking Sample of 25 ml with help of small borosilicate glass beaker. Then, for further process of sample testing filled the 'Stainless steel' container placed on Heating chamber with the existing sample in 25 ml glass beaker shown in (figure-3).

Figure-1: Glass container carrying 1 litre Machine oil.

Figure- 2: Hot air oven.

After this with full handling connect it with Insulation tester with help of Red, black and green wire shown in (figure-4). Attach their mouth with the rods of 'Stainless steel' metallic container. Then apply 500 DC voltage to the 'Stainless steel' container which are filled with lubricating oil. On the digital screen of Insulator tester, change in polarization current and change in resistance with respect to time in shown, which are the key parameters for our research work.

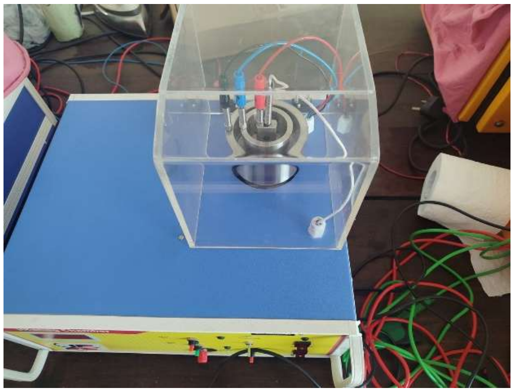

Figure-3: Heating Chamber.

Figure-3(a): Top view of Heating Chamber.

On another week, we have sample of Lubricating oil heated at 50 degrees. With same instrumental setup and with similar procedure. Again, we perform experiment and take essential readings through Insulation tester shown in figure-4. We take total three readings with same process and same instrumental setup for 40, 50 and 60 degrees Celsius.

Figure- 4: Insulator Tester.

Figure-: Readings shown by Insulator tester.

The readings we record through the camera for each sample for 600 seconds. Insulator tester records the parameters such as (PI) polarization index, (DAR) dielectric absorbtion ratio and polarization. This whole process of experimental research through instrumental setup provide us a data which is shown in table below. This data is essential for analysis of condition monitoring of lubricating oil. Further we use this data for analysing health of lubricating oil.

Table showing the Current measured in Nano Ampere(nA) of respective samples of 40°C, 50°C and 60°C with time.

S. NO.	TIME (SECONDS)	CURRENT AT 40°C	CURRENT AT 50°C	CURRENT AT 60°C
1	00:01	2.1300000000000000	2.3300000000000000	2.6200000000000000
2	00:02	2.1500000000000000	3.1700000000000000	2.3600000000000000
3	00:03	2.1300000000000000	2.3200000000000000	2.2000000000000000
4	00:04	2.1000000000000000	1.8100000000000000	2.1700000000000000
5	00:05	2.1700000000000000	1.5900000000000000	1.8800000000000000
6	00:06	2.1700000000000000	1.6600000000000000	1.6800000000000000
7	00:07	2.1800000000000000	1.6000000000000000	1.5500000000000000
8	00:08	2.1400000000000000	1.6300000000000000	1.6000000000000000
9	00:09	2.1300000000000000	1.6000000000000000	1.4700000000000000
10	00:10	2.1200000000000000	1.4500000000000000	1.4100000000000000
11	00:11	2.1300000000000000	1.4200000000000000	1.3700000000000000
12	00:12	2.1500000000000000	1.3000000000000000	1.3600000000000000
13	00:13	2.1500000000000000	1.2700000000000000	1.2000000000000000
14	00:14	2.1200000000000000	1.2000000000000000	1.3600000000000000
15	00:15	2.0700000000000000	1.2100000000000000	1.2900000000000000
16	00:16	2.0700000000000000	1.2300000000000000	1.2900000000000000
17	00:17	2.1300000000000000	1.1300000000000000	1.3900000000000000
18	00:18	2.0600000000000000	1.0200000000000000	1.3400000000000000
19	00:19	2.0700000000000000	1.0800000000000000	1.2700000000000000
20	00:20	2.0600000000000000	1.0800000000000000	1.2200000000000000
21	00:21	2.0700000000000000	1.0600000000000000	1.2600000000000000
22	00:22	2.0900000000000000	1.0100000000000000	1.2700000000000000
23	00:23	2.1300000000000000	0.9850000000000000	1.3500000000000000
24	00:24	2.1300000000000000	0.8960000000000000	1.3500000000000000
25	00:25	2.1400000000000000	0.9310000000000000	1.4200000000000000
26	00:26	2.1100000000000000	0.9600000000000000	1.4300000000000000
27	00:27	2.0600000000000000	0.8990000000000000	1.4300000000000000
28	00:28	2.0600000000000000	0.9270000000000000	1.4200000000000000
29	00:29	2.0700000000000000	0.9210000000000000	1.3600000000000000
30	00:30	2.0100000000000000	0.9270000000000000	1.5100000000000000
31	00:31	2.0600000000000000	0.9050000000000000	1.5400000000000000
32	00:32	2.0400000000000000	0.8830000000000000	1.5100000000000000
33	00:33	2.0100000000000000	0.7960000000000000	1.4800000000000000
34	00:34	2.0300000000000000	0.7800000000000000	1.5600000000000000

35	00:35	2.0500000000000000	0.7800000000000000	1.5000000000000000
36	00:36	2.0500000000000000	0.7800000000000000	1.5900000000000000
37	00:37	2.0300000000000000	0.7800000000000000	1.5300000000000000
38	00:38	2.0200000000000000	0.7800000000000000	1.4300000000000000
39	00:39	1.9800000000000000	0.7800000000000000	1.4500000000000000
40	00:40	1.9800000000000000	0.7800000000000000	1.4300000000000000
41	00:41	1.9900000000000000	0.7780000000000000	1.4200000000000000
42	00:42	1.9500000000000000	0.7770000000000000	1.3800000000000000
43	00:43	1.9500000000000000	0.7770000000000000	1.3400000000000000
44	00:44	1.9400000000000000	0.7790000000000000	1.3400000000000000
45	00:45	1.9500000000000000	0.7840000000000000	1.2900000000000000
46	00:46	1.9400000000000000	0.7960000000000000	1.2900000000000000
47	00:47	1.9800000000000000	0.8030000000000000	1.2900000000000000
48	00:48	1.9600000000000000	0.8090000000000000	1.3100000000000000
49	00:49	1.9500000000000000	0.8200000000000000	1.2100000000000000
50	00:50	1.9400000000000000	0.8200000000000000	1.2800000000000000
51	00:51	1.9300000000000000	0.8240000000000000	1.1700000000000000
52	00:52	1.9300000000000000	0.8240000000000000	1.1000000000000000
53	00:53	1.9200000000000000	0.8270000000000000	1.1000000000000000
54	00:54	1.9000000000000000	0.8290000000000000	1.0200000000000000
55	00:55	1.9100000000000000	0.8320000000000000	1.0200000000000000
56	00:56	1.9900000000000000	0.8340000000000000	1.1600000000000000
57	00:57	1.9600000000000000	0.8350000000000000	1.1500000000000000
58	00:58	1.9400000000000000	0.8340000000000000	1.0400000000000000
59	00:59	1.9500000000000000	0.8350000000000000	1.0500000000000000
60	01:00	1.9300000000000000	0.8330000000000000	1.1200000000000000
61	01:01	1.9300000000000000	0.8310000000000000	1.0600000000000000
62	01:02	1.9200000000000000	0.8300000000000000	0.9720000000000000
63	01:03	1.8900000000000000	0.8270000000000000	1.0900000000000000
64	01:04	1.8900000000000000	0.8250000000000000	1.0200000000000000
65	01:05	1.8900000000000000	0.8220000000000000	1.0200000000000000
66	01:06	1.8800000000000000	0.8190000000000000	0.9100000000000000
67	01:07	1.9100000000000000	0.8190000000000000	0.8800000000000000
68	01:08	1.9100000000000000	0.8150000000000000	0.8710000000000000
69	01:09	1.9300000000000000	0.8140000000000000	0.8140000000000000
70	01:10	1.9600000000000000	0.8120000000000000	0.8060000000000000
71	01:11	1.9300000000000000	0.8080000000000000	0.8840000000000000
72	01:12	1.9100000000000000	0.8040000000000000	0.8790000000000000
73	01:13	1.9100000000000000	0.8010000000000000	0.9290000000000000
74	01:14	1.8900000000000000	0.7980000000000000	0.8710000000000000
75	01:15	1.8900000000000000	0.7940000000000000	0.9040000000000000
76	01:16	1.8900000000000000	0.7900000000000000	0.8540000000000000
77	01:17	1.9000000000000000	0.7860000000000000	0.8730000000000000
78	01:18	1.8700000000000000	0.7760000000000000	0.8800000000000000
79	01:19	1.8600000000000000	0.7670000000000000	0.8810000000000000
80	01:20	1.8600000000000000	0.7640000000000000	0.9050000000000000
81	01:21	1.9000000000000000	0.7600000000000000	0.8360000000000000
82	01:22	1.8800000000000000	0.7610000000000000	0.8490000000000000
83	01:23	1.8900000000000000	0.7600000000000000	0.8470000000000000
84	01:24	1.8700000000000000	0.7590000000000000	0.8930000000000000

85	01:25	1.8400000000000000	0.7570000000000000	0.9740000000000000
86	01:26	1.8300000000000000	0.7560000000000000	0.8670000000000000
87	01:27	1.8100000000000000	0.7560000000000000	0.8350000000000000
88	01:28	1.8100000000000000	0.7490000000000000	0.8090000000000000
89	01:29	1.8000000000000000	0.7450000000000000	0.7870000000000000
90	01:30	1.8000000000000000	0.7360000000000000	0.8430000000000000
91	01:31	1.7900000000000000	0.7360000000000000	0.8710000000000000
92	01:32	1.7800000000000000	0.7290000000000000	0.9060000000000000
93	01:33	1.7500000000000000	0.7290000000000000	1.0800000000000000
94	01:34	1.7800000000000000	0.7270000000000000	1.0800000000000000
95	01:35	1.7800000000000000	0.7250000000000000	0.8090000000000000
96	01:36	1.7700000000000000	0.7220000000000000	0.8340000000000000
97	01:37	1.7800000000000000	0.7180000000000000	0.7960000000000000
98	01:38	1.7900000000000000	0.7200000000000000	0.8040000000000000
99	01:39	1.8000000000000000	0.7170000000000000	0.7640000000000000
100	01:40	1.7800000000000000	0.7170000000000000	0.7640000000000000
101	01:41	1.7400000000000000	0.7150000000000000	0.7640000000000000
102	01:42	1.7400000000000000	0.7140000000000000	0.7640000000000000
103	01:43	1.7400000000000000	0.7130000000000000	0.7640000000000000
104	01:44	1.7500000000000000	0.7120000000000000	0.7640000000000000
105	01:45	1.7500000000000000	0.7110000000000000	0.7640000000000000
106	01:46	1.8800000000000000	0.7100000000000000	0.7950000000000000
107	01:47	1.8400000000000000	0.7090000000000000	0.8200000000000000
108	01:48	1.8000000000000000	0.7080000000000000	0.8490000000000000
109	01:49	1.8400000000000000	0.7070000000000000	0.8800000000000000
110	01:50	1.8100000000000000	0.7050000000000000	0.9100000000000000
111	01:51	1.7600000000000000	0.7039999999999999	0.9400000000000000
112	01:52	1.7600000000000000	0.7009999999999999	0.9690000000000000
113	01:53	1.8100000000000000	0.6989999999999999	0.9970000000000000
114	01:54	1.7700000000000000	0.6959999999999999	1.0200000000000000
115	01:55	1.7900000000000000	0.6939999999999999	1.0500000000000000
116	01:56	1.7400000000000000	0.6919999999999999	1.0800000000000000
117	01:57	1.7300000000000000	0.6899999999999999	1.1100000000000000
118	01:58	1.7100000000000000	0.6889999999999999	1.1400000000000000
119	01:59	1.7300000000000000	0.6870000000000001	1.1800000000000000
120	02:00	1.7400000000000000	0.6830000000000001	1.1800000000000000
121	02:01	1.7400000000000000	0.6790000000000001	1.1900000000000000
122	02:02	1.7300000000000000	0.6740000000000001	1.2100000000000000
123	02:03	1.7400000000000000	0.6690000000000000	1.2100000000000000
124	02:04	1.7400000000000000	0.6620000000000000	1.2100000000000000
125	02:05	1.7400000000000000	0.6560000000000000	1.2000000000000000
126	02:06	1.7500000000000000	0.6500000000000000	1.2000000000000000
127	02:07	1.7300000000000000	0.6440000000000000	1.1900000000000000
128	02:08	1.7100000000000000	0.6380000000000000	1.1800000000000000
129	02:09	1.7100000000000000	0.6320000000000000	1.1600000000000000
130	02:10	1.7100000000000000	0.6260000000000000	1.1500000000000000
131	02:11	1.7400000000000000	0.6210000000000000	1.1500000000000000
132	02:12	1.6700000000000000	0.6160000000000000	1.1400000000000000
133	02:13	1.6800000000000000	0.6110000000000000	1.1400000000000000
134	02:14	1.7000000000000000	0.6080000000000000	1.1400000000000000

135	02:15	1.7200000000000000	0.6060000000000000	1.1400000000000000
136	02:16	1.7200000000000000	0.6040000000000000	1.1400000000000000
137	02:17	1.7000000000000000	0.6040000000000000	1.1500000000000000
138	02:18	1.7100000000000000	0.6060000000000000	1.1500000000000000
139	02:19	1.7000000000000000	0.6060000000000000	1.1600000000000000
140	02:20	1.7200000000000000	0.6080000000000000	1.1600000000000000
141	02:21	1.7200000000000000	0.6130000000000000	1.1700000000000000
142	02:22	1.6900000000000000	0.6130000000000000	1.1700000000000000
143	02:23	1.6800000000000000	0.6160000000000000	1.1800000000000000
144	02:24	1.6800000000000000	0.6190000000000000	1.2000000000000000
145	02:25	1.7300000000000000	0.6220000000000000	1.2100000000000000
146	02:26	1.7200000000000000	0.6240000000000000	1.2200000000000000
147	02:27	1.7100000000000000	0.6270000000000000	1.2400000000000000
148	02:28	1.7100000000000000	0.6300000000000000	1.2400000000000000
149	02:29	1.7800000000000000	0.6330000000000000	1.2500000000000000
150	02:30	1.7400000000000000	0.6360000000000000	1.2500000000000000
151	02:31	1.7100000000000000	0.6390000000000000	1.2500000000000000
152	02:32	1.7100000000000000	0.6460000000000000	1.2500000000000000
153	02:33	1.6700000000000000	0.6550000000000000	1.2400000000000000
154	02:34	1.6800000000000000	0.6660000000000000	1.2400000000000000
155	02:35	1.6700000000000000	0.6780000000000001	1.2300000000000000
156	02:36	1.6500000000000000	0.6889999999999999	1.2200000000000000
157	02:37	1.6400000000000000	0.6989999999999999	1.2100000000000000
158	02:38	1.6800000000000000	0.7070000000000000	1.2000000000000000
159	02:39	1.6800000000000000	0.7110000000000000	1.1900000000000000
160	02:40	1.6800000000000000	0.7120000000000000	1.1900000000000000
161	02:41	1.6400000000000000	0.7100000000000000	1.1800000000000000
162	02:42	1.6400000000000000	0.7039999999999999	1.1800000000000000
163	02:43	1.6400000000000000	0.6969999999999999	1.1800000000000000
164	02:44	1.6600000000000000	0.6879999999999999	1.1800000000000000
165	02:45	1.6400000000000000	0.6780000000000001	1.1800000000000000
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168	02:48	1.6400000000000000	0.6490000000000000	1.1500000000000000
169	02:49	1.6400000000000000	0.6410000000000000	1.1400000000000000
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171	02:51	1.6200000000000000	0.6250000000000000	1.1100000000000000
172	02:52	1.6300000000000000	0.6180000000000000	1.0900000000000000
173	02:53	1.6200000000000000	0.6120000000000000	1.0700000000000000
174	02:54	1.6300000000000000	0.6060000000000000	1.0600000000000000
175	02:55	1.6200000000000000	0.6000000000000000	1.0400000000000000
176	02:56	1.6300000000000000	0.5950000000000000	1.0300000000000000
177	02:57	1.6200000000000000	0.5910000000000000	1.0200000000000000
178	02:58	1.6300000000000000	0.5870000000000000	1.0100000000000000
179	02:59	1.6400000000000000	0.5830000000000000	0.9980000000000000
180	03:00	1.6100000000000000	0.5789999999999999	0.9920000000000000
181	03:01	1.6300000000000000	0.5749999999999999	0.9880000000000000
182	03:02	1.6400000000000000	0.5719999999999999	0.9830000000000000
183	03:03	1.6500000000000000	0.5679999999999999	0.9790000000000000
184	03:04	1.6500000000000000	0.5639999999999999	0.9750000000000000

185	03:05	1.6600000000000000	0.5610000000000001	0.9710000000000000
186	03:06	1.6500000000000000	0.5580000000000001	0.9670000000000000
187	03:07	1.6400000000000000	0.5550000000000001	0.9650000000000000
188	03:08	1.6200000000000000	0.5540000000000001	0.9650000000000000
189	03:09	1.6200000000000000	0.5540000000000001	0.9680000000000000
190	03:10	1.6300000000000000	0.5550000000000001	0.9740000000000000
191	03:11	1.6100000000000000	0.5550000000000001	0.9800000000000000
192	03:12	1.6100000000000000	0.5560000000000001	0.9880000000000000
193	03:13	1.6500000000000000	0.5570000000000001	0.9810000000000000
194	03:14	1.6100000000000000	0.5590000000000001	0.9970000000000000
195	03:15	1.5900000000000000	0.5600000000000001	1.0100000000000000
196	03:16	1.6100000000000000	0.5620000000000001	1.0100000000000000
197	03:17	1.6000000000000000	0.5639999999999999	1.0200000000000000
198	03:18	1.6000000000000000	0.5649999999999999	1.0200000000000000
199	03:19	1.6000000000000000	0.5669999999999999	1.0300000000000000
200	03:20	1.6000000000000000	0.5669999999999999	1.0300000000000000
201	03:21	1.6000000000000000	0.5689999999999999	1.0400000000000000
202	03:22	1.6000000000000000	0.5699999999999999	1.0400000000000000
203	03:23	1.6100000000000000	0.5699999999999999	1.0400000000000000
204	03:24	1.6200000000000000	0.5709999999999999	1.0400000000000000
205	03:25	1.6200000000000000	0.5709999999999999	1.0400000000000000
206	03:26	1.6000000000000000	0.5709999999999999	1.0300000000000000
207	03:27	1.5900000000000000	0.5709999999999999	1.0300000000000000
208	03:28	1.6000000000000000	0.5709999999999999	1.0300000000000000
209	03:29	1.5900000000000000	0.5709999999999999	1.0300000000000000
210	03:30	1.5900000000000000	0.5709999999999999	1.0300000000000000
211	03:31	1.6000000000000000	0.5719999999999999	1.0200000000000000
212	03:32	1.6000000000000000	0.5719999999999999	1.0200000000000000
213	03:33	1.6000000000000000	0.5709999999999999	1.0200000000000000
214	03:34	1.6000000000000000	0.5699999999999999	1.0200000000000000
215	03:35	1.5900000000000000	0.5699999999999999	1.0200000000000000
216	03:36	1.5800000000000000	0.5679999999999999	1.0100000000000000
217	03:37	1.5800000000000000	0.5669999999999999	1.0100000000000000
218	03:38	1.5700000000000000	0.5620000000000001	1.0100000000000000
219	03:39	1.5700000000000000	0.5600000000000001	1.0000000000000000
220	03:40	1.5800000000000000	0.5620000000000001	0.9950000000000000
221	03:41	1.5800000000000000	0.5580000000000001	0.9890000000000000
222	03:42	1.5800000000000000	0.5570000000000001	0.9800000000000000
223	03:43	1.5800000000000000	5.5560000000000000	0.9710000000000000
224	03:44	1.5900000000000000	0.5550000000000001	0.9610000000000000
225	03:45	1.5700000000000000	0.5540000000000001	0.9510000000000000
226	03:46	1.5700000000000000	0.5540000000000001	0.9420000000000000
227	03:47	1.5700000000000000	0.5540000000000001	0.9340000000000000
228	03:48	1.5800000000000000	0.5540000000000001	0.9270000000000000
229	03:49	1.6000000000000000	0.5540000000000001	0.9210000000000000
230	03:50	1.5600000000000000	0.5550000000000001	0.9150000000000000
231	03:51	1.6300000000000000	0.5560000000000001	0.9080000000000000
232	03:52	1.5500000000000000	0.5580000000000001	0.9010000000000000
233	03:53	1.5500000000000000	0.5580000000000001	0.8940000000000000
234	03:54	1.5300000000000000	0.5600000000000001	0.8870000000000000

235	03:55	1.5300000000000000	0.5610000000000001	0.8800000000000000
236	03:56	1.5400000000000000	0.5629999999999999	0.8730000000000000
237	03:57	1.5200000000000000	0.5639999999999999	0.8650000000000000
238	03:58	1.5200000000000000	0.5649999999999999	0.8560000000000000
239	03:59	1.5200000000000000	0.5669999999999999	0.8470000000000000
240	04:00	1.5300000000000000	0.5669999999999999	0.8380000000000000
241	04:01	1.5200000000000000	0.5669999999999999	0.8300000000000000
242	04:02	1.5200000000000000	0.5669999999999999	0.8200000000000000
243	04:03	1.5200000000000000	0.5669999999999999	0.8130000000000000
244	04:04	1.5200000000000000	0.5669999999999999	0.8080000000000000
245	04:05	1.5000000000000000	0.5669999999999999	0.8060000000000000
246	04:06	1.5000000000000000	0.5669999999999999	0.7980000000000000
247	04:07	1.5000000000000000	0.5659999999999999	0.7910000000000000
248	04:08	1.5000000000000000	0.5649999999999999	0.7850000000000000
249	04:09	1.4900000000000000	0.5639999999999999	0.7780000000000000
250	04:10	1.1490000000000000	0.5620000000000001	0.7720000000000000
251	04:11	1.4900000000000000	0.5600000000000001	0.7660000000000000
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253	04:13	1.4800000000000000	0.5550000000000001	0.7550000000000000
254	04:14	1.4900000000000000	0.5500000000000001	0.7490000000000000
255	04:15	1.4700000000000000	0.5470000000000001	0.7440000000000000
256	04:16	1.1490000000000000	0.5440000000000000	0.7400000000000000
257	04:17	1.4800000000000000	0.5440000000000000	0.7360000000000000
258	04:18	1.4800000000000000	0.5410000000000000	0.7320000000000000
259	04:19	1.4800000000000000	0.5380000000000000	0.7270000000000000
260	04:20	1.4700000000000000	0.5350000000000000	0.7220000000000000
261	04:21	1.4700000000000000	0.5320000000000000	0.7170000000000000
262	04:22	1.4700000000000000	0.5300000000000000	0.7120000000000000
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265	04:25	1.4500000000000000	0.5230000000000000	0.6949999999999999
266	04:26	1.4500000000000000	0.5210000000000000	0.6909999999999999
267	04:27	1.4400000000000000	0.5190000000000000	0.6870000000000001
268	04:28	1.4400000000000000	0.5170000000000000	0.6840000000000001
269	04:29	1.4700000000000000	0.5160000000000000	0.6810000000000001
270	04:30	1.4800000000000000	0.5140000000000000	0.6800000000000001
271	04:31	1.5000000000000000	0.5130000000000000	0.6800000000000001
272	04:32	1.4700000000000000	0.5100000000000000	0.6820000000000001
273	04:33	1.4800000000000000	0.5080000000000000	0.6850000000000001
274	04:34	1.1470000000000000	0.5060000000000000	0.6889999999999999
275	04:35	1.4900000000000000	0.5030000000000000	0.6919999999999999
276	04:36	1.4600000000000000	0.5010000000000000	0.6939999999999999
277	04:37	1.4600000000000000	0.4990000000000000	0.6939999999999999
278	04:38	1.4500000000000000	0.4960000000000000	0.6929999999999999
279	04:39	1.4400000000000000	0.4940000000000000	0.6879999999999999
280	04:40	1.4400000000000000	0.4920000000000000	0.6840000000000001
281	04:41	1.4200000000000000	0.4900000000000000	0.6840000000000001
282	04:42	1.4500000000000000	0.4880000000000000	0.6800000000000001
283	04:43	1.4400000000000000	0.4860000000000000	0.6760000000000001
284	04:44	1.4300000000000000	0.4850000000000000	0.6720000000000001

285	04:45	1.4300000000000000	0.4840000000000000	0.6680000000000000
286	04:46	1.4300000000000000	0.4840000000000000	0.6640000000000000
287	04:47	1.4200000000000000	0.4840000000000000	0.6600000000000000
288	04:48	1.4400000000000000	0.4840000000000000	0.6560000000000000
289	04:49	1.4200000000000000	0.4840000000000000	0.6530000000000000
290	04:50	1.4000000000000000	0.4840000000000000	0.6490000000000000
291	04:51	1.4000000000000000	0.4830000000000000	0.6460000000000000
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306	05:06	1.3800000000000000	0.4680000000000000	0.6120000000000000
307	05:07	1.3800000000000000	0.4670000000000000	0.6100000000000000
308	05:08	1.3700000000000000	0.4670000000000000	0.6080000000000000
309	05:09	1.3700000000000000	0.4670000000000000	0.6060000000000000
310	05:10	1.4000000000000000	0.4670000000000000	0.6040000000000000
311	05:11	1.4300000000000000	0.4660000000000000	0.6020000000000000
312	05:12	1.3800000000000000	0.4660000000000000	0.6000000000000000
313	05:13	1.3800000000000000	0.4660000000000000	0.5990000000000000
314	05:14	1.3700000000000000	0.4650000000000000	0.5990000000000000
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319	05:19	1.4100000000000000	0.4630000000000000	0.6280000000000000
320	05:20	1.4100000000000000	0.4620000000000000	0.6390000000000000
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322	05:22	1.4300000000000000	0.4610000000000000	0.6630000000000000
323	05:23	1.4300000000000000	0.4600000000000000	0.6770000000000001
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325	05:25	1.4300000000000000	0.4590000000000000	0.7320000000000000
326	05:26	1.4100000000000000	0.4580000000000000	0.7320000000000000
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329	05:29	1.3600000000000000	0.4560000000000000	0.8020000000000000
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332	05:32	1.3500000000000000	0.4540000000000000	0.8760000000000000
333	05:33	1.3500000000000000	0.4530000000000000	0.9000000000000000
334	05:34	1.3600000000000000	0.4530000000000000	0.9220000000000000

335	05:35	1.3600000000000000	0.4530000000000000	0.9420000000000000
336	05:36	1.3500000000000000	0.4530000000000000	0.9590000000000000
337	05:37	1.3600000000000000	0.4540000000000000	0.9740000000000000
338	05:38	1.3500000000000000	0.4540000000000000	0.9870000000000000
339	05:39	1.3600000000000000	0.4550000000000000	0.9980000000000000
340	05:40	1.3600000000000000	0.4550000000000000	1.0100000000000000
341	05:41	1.3600000000000000	0.4560000000000000	1.0200000000000000
342	05:42	1.3500000000000000	0.4560000000000000	1.0200000000000000
343	05:43	1.3500000000000000	0.4570000000000000	1.0300000000000000
344	05:44	1.3400000000000000	0.4570000000000000	1.0300000000000000
345	05:45	1.3400000000000000	0.4570000000000000	1.0300000000000000
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353	05:53	1.3200000000000000	0.4930000000000000	1.0000000000000000
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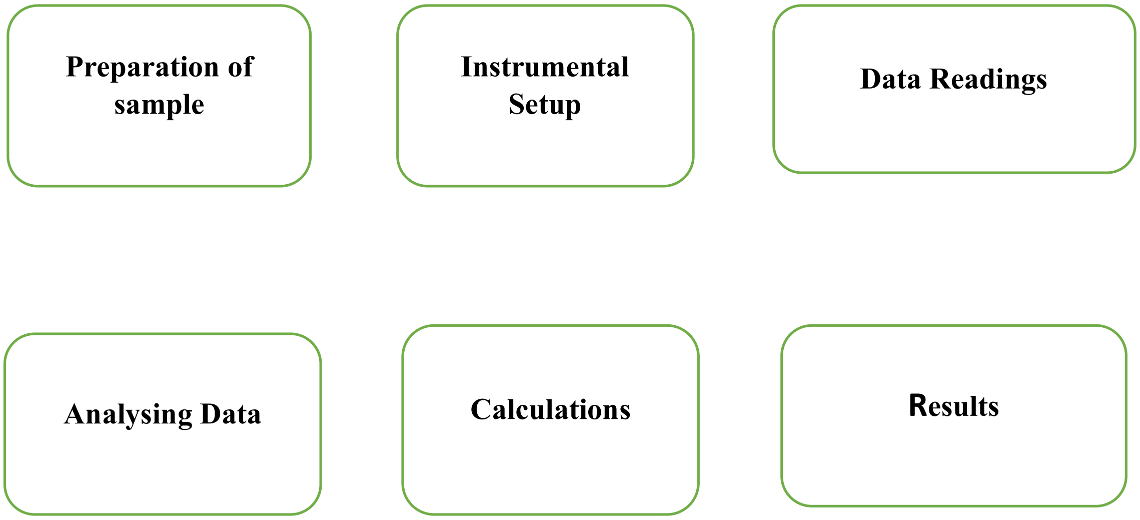
358	05:58	1.3000000000000000	0.5360000000000000	0.9880000000000000
359	05:59	1.3000000000000000	0.5450000000000000	0.9880000000000000
360	06:00	1.3000000000000000	0.5450000000000000	0.9890000000000000
361	06:01	1.3000000000000000	0.5520000000000001	0.9910000000000000
362	06:02	1.2900000000000000	0.5600000000000001	0.9930000000000000
363	06:03	1.2900000000000000	0.5659999999999999	0.9960000000000000
364	06:04	1.2900000000000000	0.5719999999999999	0.9960000000000000
365	06:05	1.2800000000000000	0.5769999999999999	0.9950000000000000
366	06:06	1.2900000000000000	0.5810000000000000	0.9930000000000000
367	06:07	1.2900000000000000	0.5840000000000000	0.9900000000000000
368	06:08	1.2800000000000000	0.5860000000000000	0.9880000000000000
369	06:09	1.2700000000000000	0.5870000000000000	0.9860000000000000
370	06:10	1.2700000000000000	0.5880000000000000	0.9860000000000000
371	06:11	1.2700000000000000	0.5870000000000000	0.9860000000000000
372	06:12	1.2600000000000000	0.5860000000000000	0.9880000000000000
373	06:13	1.2600000000000000	0.5850000000000000	0.9880000000000000
374	06:14	1.2600000000000000	0.5830000000000000	0.9900000000000000
375	06:15	1.2600000000000000	0.5820000000000000	0.9920000000000000
376	06:16	1.2600000000000000	0.5800000000000000	0.9940000000000000
377	06:17	1.2600000000000000	0.5779999999999999	0.9960000000000000
378	06:18	1.2500000000000000	0.5759999999999999	0.9980000000000000
379	06:19	1.2500000000000000	0.5739999999999999	0.9980000000000000
380	06:20	1.2400000000000000	0.5719999999999999	0.9970000000000000
381	06:21	1.2400000000000000	0.5689999999999999	0.9940000000000000
382	06:22	1.2400000000000000	0.5669999999999999	0.9900000000000000
383	06:23	1.2400000000000000	0.5649999999999999	0.9860000000000000
384	06:24	1.2500000000000000	0.5629999999999999	0.9810000000000000

Flow Chart showing testing process:



2.3 Observations and Analysis:

1st week (40°C sample): The polarization current exhibited a downward trend with minor upward deflections. This suggests moderate aging effects, where thermal exposure initiates molecular breakdown but retains some insulation capacity.

2nd week (50°C sample): The polarization current showed significant upward variations, indicating substantial breakdown of insulating properties. This was accompanied by frequent deflections in resistivity, suggesting increased ionic mobility and altered molecular interactions.

3rd week (60°C sample): The behaviour was consistently showing higher variations as the increasing value in polarisation current reaffirming that further thermal stress exacerbates molecular degradation, reducing the dielectric strength and resistivity of the oil.

The experimental results indicate that thermal aging induced by excessive heating accelerates oxidative degradation, molecular dissociation and acid formation within lubricating oil. The observed increase in polarization current with temperature correlates with a decline in resistivity, implying a loss of insulating characteristics. This degradation is primarily due to the formation of conductive by products, such as free radicals and charged particles, which enhance electrical conductivity and reduce dielectric stability. The findings underscore the necessity for monitoring lubricating oil condition in high-temperature environments, as prolonged exposure may compromise its ability to function as an effective insulating and lubricating medium. Thermal aging of lubricating oil refers to the degradation that occurs when the oil is subjected to prolonged exposure to high temperatures. Over time, this heat accelerates oxidation reactions, breaking down the base oil molecules and depleting crucial additives like antioxidants and detergents. As a result, the oil’s viscosity increases due to the formation of heavier oxidation products, and its Total Acid Number (TAN) rises as acidic byproducts accumulate. Sludge, varnish, and insoluble compounds may form, which can clog filters and impair lubrication. The oil’s ability to form a stable film on metal surfaces also diminishes, increasing wear and risk of failure in machinery. In systems like transformers or marine engines, thermal aging can further lead to increased electrical conductivity and deposit buildup, jeopardizing insulation and safety. Overall, thermal aging reduces the oil’s performance, longevity, and protective qualities—necessitating close monitoring and timely replacement in condition-based maintenance strategies.

CHAPTER- 3

RESULTS AND DISCUSSION

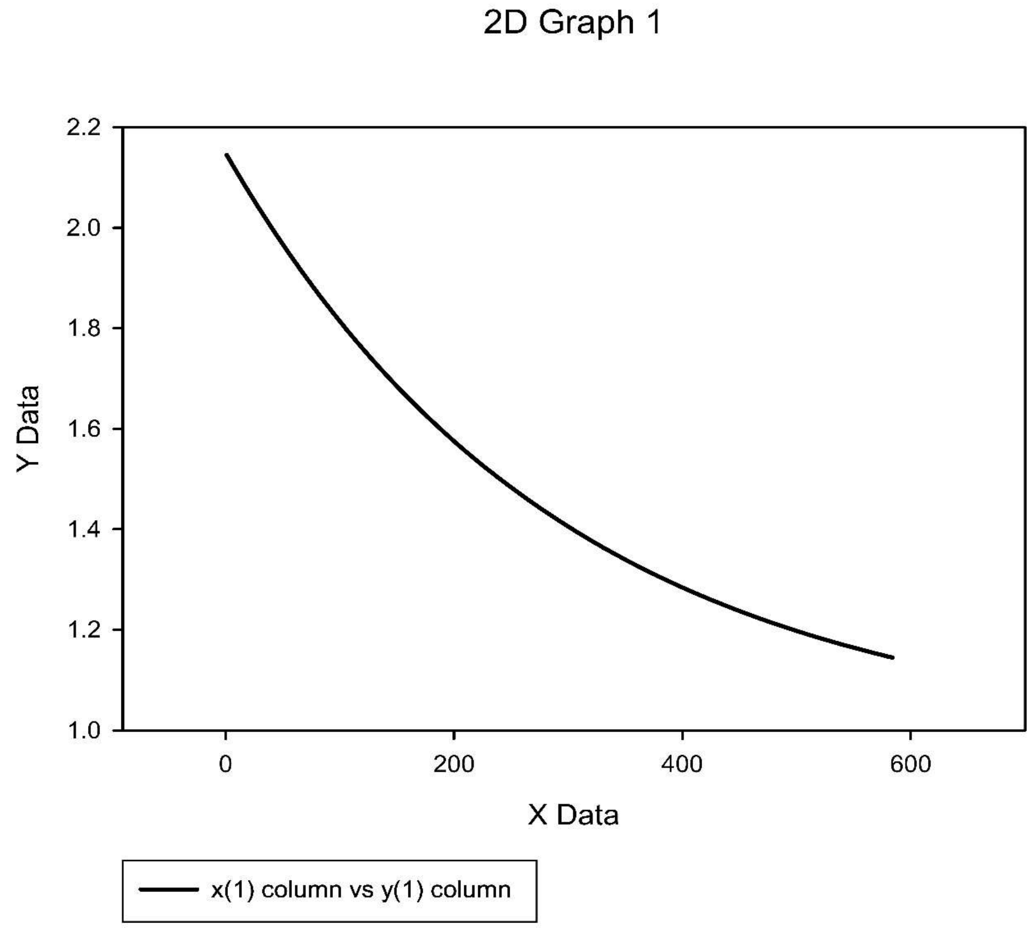


Figure-5: Polarization Current

This graph is made through the help of resulting measuring current of all respected samples mentioned in above given table. It is developed with the use of curve fitting of current by using sigma plot software. The graph shows a downward trend in polarization current typically indicates that the dielectric material is relaxing over time after being energized, this is expected as trapped charges recombine or redistribute. The minor upward deflections, however, are telling. These blips suggest intermittent processes such as re-polarization due to structural rearrangements or localized charge injection sites becoming active. At 40 °c, lubricating oil in a moderate thermal regime. It's not extreme enough for catastrophic breakdown, but it's sufficient to mobilize certain dipolar molecular groups. Initiate slow oxidation or moisture-related chemical changes in insulating oils or solids. Cause minor molecular scission, which can form polar degradation products, these slightly increase conductivity temporarily, hence the upward deflections. Moderate aging interpretation is the molecular breakdown likely observing early-stage chain scission or crosslinking, where polymer chains start fragmenting but the matrix still retains bulk integrity. It is residual the insulation strength despite the aging onset, the material hasn't reached a runaway degradation phase. Hence, polarization current continues to generally decay.

3.1 Thermal Aging Effects:

The increasing polarization current with temperature (40°C → 60°C) indicates molecular breakdown and reduced resistivity. This suggests higher ionic mobility, meaning that degradation products affect the insulating properties of the lubricating oil. where its molecules start breaking down. This breakdown leads to a higher polarization current and lower electrical resistivity. In simple terms, more ions are free to move around, showing that the oil is degrading and losing its ability to insulate effectively. as temperature rises, the oil's molecules start to break apart. This releases free ions that can carry electrical charge more easily, hence the increase in polarization current. At the same time, the oil becomes less effective as an insulator because these free ions reduce resistivity. It's a sign that the oil's insulating strength is being compromised due to the formation of acid, moisture etc.

In condition-based maintenance (CBM), the following are tracked to assess thermal aging

Parameter	**Diagnostic Insight**
TAN/TBN	Oil degradation and acidity
Viscosity Index	Flow and lubrication behaviour
FTIR Spectroscopy	Oxidation products and additives
Dielectric Constant	Moisture and oxidation level
Insolubles Sludge	Contaminant buildup
Colorimetry	Visual cue of oxidation severity

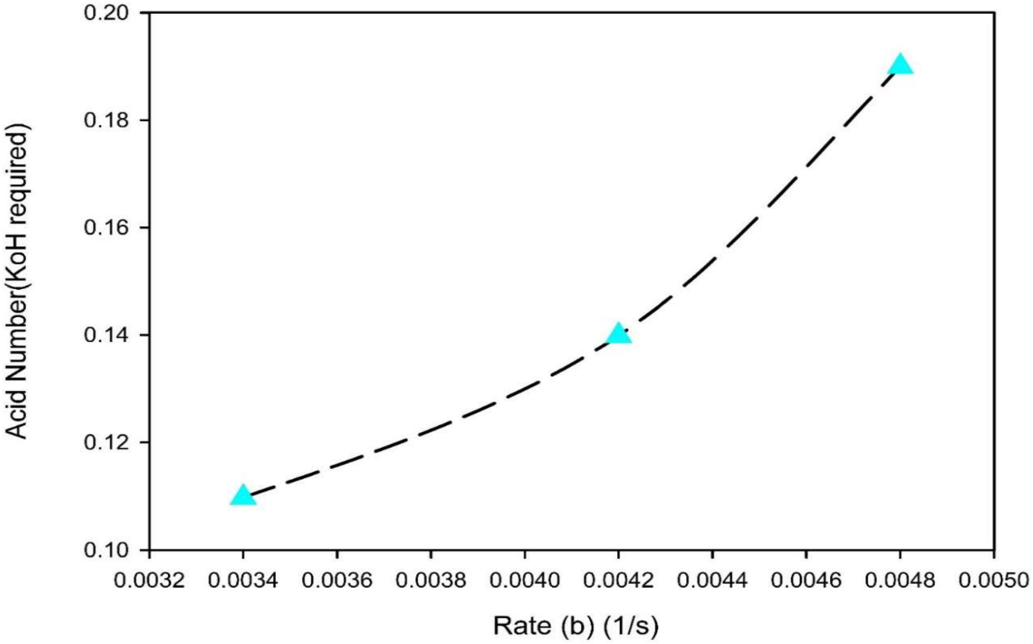


Figure-6: Graph of Sample tested at 40 Degree

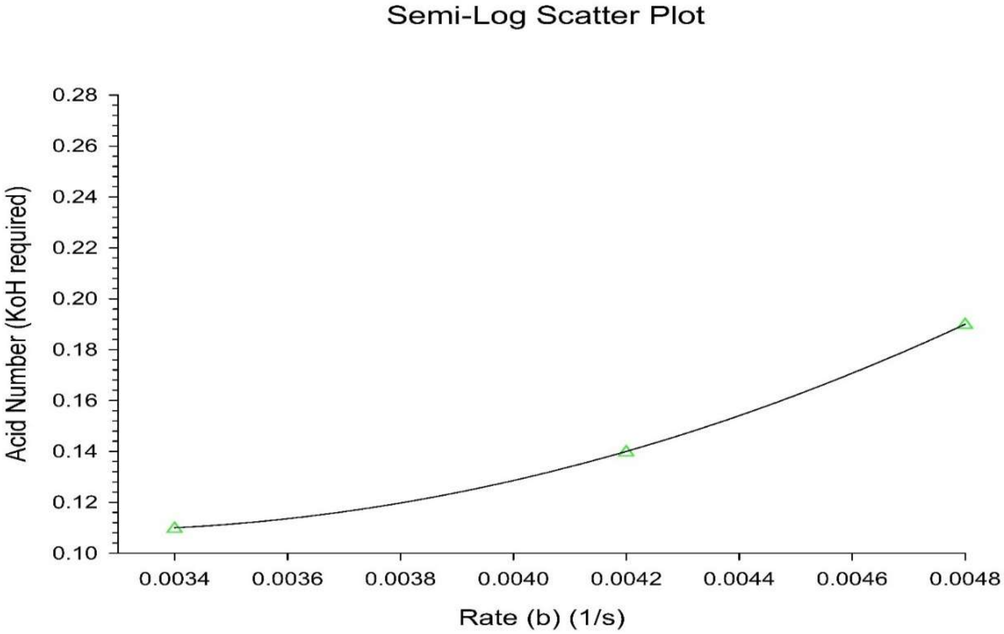


Figure- 6: Graph of Sample tested at 50 Degree.

This graph illustrating the relationship between the rate (b) (in 1/s) and the acid number (measured in KoH required). The x-axis represents the rate, ranging from 0.0034 to 0.0048, while the y-axis represents the acid number, ranging from 0.10 to 0.28. The green triangles represent data points, which are connected by a smooth curve. The curve indicates a positive correlation between the rate (b) and the acid number as the rate increases, the acid number also rises. The acid number reflects the amount of potassium hydroxide (KoH) required to neutralize the acid produced. A higher acid number suggests increased acidic degradation of the lubricating oil. This graph could be used to analyse acid formation over time, possibly due to thermal aging or chemical degradation. Related to lubricating oil research, it might indicate how oil oxidation accelerates, leading to increased acidity with a rising rate.

3.2 Correlation Between Polarization Current and Acid Number Analysis:

Polarization current experiment evaluates lubricating oil degradation due to thermal aging. The graph you provided shows a positive correlation between the reaction rate (b) and acid number, which suggests the progression of oxidative degradation and acid formation. The correlation between polarization current and acid number lies in their shared sensitivity to changes in lubricating oil chemistry—especially degradation.

Acid Number (AN) measures the concentration of acidic compounds in oil, which increases due to oxidation, additive breakdown, or contamination.

Polarization Current (Ip) reflects the movement of ions under an electric field and is influenced by the oil’s dielectric properties. As oil degrades, increased polar compounds (like acids) raise conductivity, which affects polarization current.

Correlation: As acid number rises, indicating more acidic by-products, the polarization current typically increases due to the higher ionic content. This makes polarization current a potential indirect, real-time measure of oil acidity and health.

Example 1:

Oil A starts with an acid number of 0.3 mg KOH/g and a polarization current of 0.1 μ A. After 300 operating hours, Oil A shows acid number of 1.2 mg KOH/g and polarization current of 0.45 μ A. This upward trend in both values shows a direct correlation, suggesting polarization current can serve as an early warning for acid buildup and oil degradation.

Example 2:

Observing the polarization current of a lubricating oil sample:

At the start, the polarization current measure is 150 n A (Nano Ampere). After some use, it increases to 1.2 µ A (Micro Ampere). Since 1 µ A = 1000 n A → 1.2 µ A = 1200 n A.

So, the current increased from 150 n A to 1200 n A, which is 8 times increase. That tells you the oil is accumulating more conductive (and potentially corrosive) by product maybe due to oxidation or contamination, validating the upward trend in the acid number too.

3.3 Rate vs. Acid Number:

Graph Analysis (Rate vs. Acid Number):

The acid number increases as the rate rises, reflecting the formation of acidic compounds. In thermal aging, oxidative reactions produce carboxylic acids, contributing to rising acidity.

Both analyses reinforce the idea that thermal aging accelerates oxidation, leading to higher ionic mobility, increasing polarization current. Formation of acidic byproducts, increasing acid number over time. The relationship between rate and acid number becomes especially relevant when studying the degradation of lubricating oils or other organic compounds over time. Acid Number (AN) reflects the amount of acidic compounds in a substance typically increasing as oil oxidizes or breaks down. Rate refers to how quickly a chemical change occurs, often influenced by temperature, concentration, and catalysts. The connection is as oil degrades, oxidation reactions produce acidic by-products. The rate at which the acids form directly affects how quickly the acid number increases. In a high-temperature lubrication oil exposed to oxygen and heat undergoes oxidation. If the oxidation and chemical reaction is high due to elevated temperature the acid number will climb rapidly. This indicates that there is faster oil degradation and the need for earlier replacement. So, monitoring the acid number over time gives insight into the underlying kinetics of oil breakdown.

To find the Acid Number (KoH) using the formula $y = a x + bx^2$, where the "Rate" is likely a function of time (represented by x). To calculate this, we need values of coefficients a and b which describe how the acid number changes with x. By putting these values o into the equation, we get the corresponding Acid Number. With the help of graph analysis, we get the coefficient values by using software called sigma plot.

CHAPTER - 4

CONCLUSION AND FUTURE SCOPE

4.1 Conclusion:

The use of polarization current as a diagnostic tool for condition monitoring of lubrication oil offers a highly effective and non-invasive method to assess the oil's degradation and contamination levels in real time. This method provides a comprehensive insight into several critical parameters that directly impact the performance and longevity of machinery. All parameters which affect lubricating oil such as oxidation level, acid level gas formation, moisture content and particle contamination are carried out by the measurements of dipoles behavior of polarization current. An increase in polarization current correlates with a rise in the oil's acidity due to additive depletion or oxidation, indicating corrosive tendencies. Polarization measurements detect by-products of oxidation that affect the dielectric properties of the oil, offering early warning of oil aging and performance loss. The formation of gases such as co, co_2, and hydrocarbons alters the conductivity of the oil. Polarization current can indirectly reflect this change by variations in current flow. Water contamination drastically affects the polarization current due to its higher dielectric constant, making this method sensitive and reliable for detecting even trace moisture. Metal particles and wear debris influence the conductive pathways in oil. Higher polarization current can indicate increased particle presence, which is critical for wear analysis. Overall, polarization current analysis serves as a fast, cost-effective, and sensitive technique for in-situ oil quality assessment. It helps in predictive maintenance, reducing downtime, preventing machinery failure, and extending the service life of lubricants. Integrating this method with traditional oil analysis techniques enhances the reliability of condition-based monitoring and supports informed decision-making for maintenance schedules. Polarization current offers a promising diagnostic tool for assessing oil degradation, particularly by correlating the acid number with the rate. This relationship reflects chemical changes due to oxidation, contamination, and additive depletion. Over time, consistent tracking reveals trends that help predict oil failure, enabling proactive maintenance. Moreover, with continuous research and refinement, other critical parameters—such as moisture content, varnish potential, dielectric strength, and metal wear particles—can be integrated into the monitoring framework. Together, these multidimensional insights enhance the reliability and lifespan of machinery, reduce downtime, and ensure optimal performance.

4.2 FUTURE SCOPE:

The application of polarization current for lubrication oil condition monitoring holds tremendous potential for expansion and innovation in multiple industrial sectors. As industries continue to demand higher equipment reliability, predictive maintenance, and real-time health monitoring, polarization current-based diagnostics can evolve in the following broad directions:

1. Integration with IoT and Industry

Future systems will integrate polarization current sensors with IoT devices for real-time, remote monitoring of lubricant condition. Continuous data acquisition combined with cloud platforms will enable predictive analytics and machine learning models to forecast lubricant degradation trends and maintenance needs more accurately. Smart sensors embedded in machinery will autonomously collect, transmit, and analyse polarization data, enabling fully automated lubrication management systems.

2. Advanced Sensor Technology

Development of miniaturized, highly sensitive, and low-cost sensors will make polarization current monitoring more accessible across industries. Next-generation sensors will have improved sensitivity to minor fluctuations in oil properties, allowing earlier detection of potential failures. Portable handheld devices based on polarization current will become standard diagnostic tools for field engineers.

3. Hybrid Diagnostic Systems

Combining polarization current analysis with other diagnostic methods such as FTIR (Fourier Transform Infrared Spectroscopy), TAN measurement, particle counting, and dissolved gas analysis will provide a more comprehensive oil health profile. Multivariate analysis models will integrate various parameters to offer holistic condition assessments.

4. Application to Emerging Lubricants

As synthetic, bio-based, and advanced formulation lubricants become more prevalent, polarization current techniques can be adapted to monitor the unique degradation mechanisms of these new oils. Research will focus on developing calibration standards and algorithms tailored to diverse lubricant chemistries.

5. Artificial Intelligence and Big Data Utilization

AI and deep learning algorithms can analyse massive datasets of polarization current readings to identify complex patterns of oil degradation. Predictive models can provide failure prediction windows for specific components, reducing unplanned downtime. Digital twins of lubrication systems may use polarization current data to simulate and optimize lubrication performance in real-time.

6. Wider Industrial Adoption

Polarization current monitoring will see increased adoption across industries such as marine, aerospace, wind energy, mining, heavy manufacturing, and automotive sectors where lubricant performance is critical. The technique will also play a key role in nuclear and high-voltage equipment, where dielectric properties of lubricating oils are vital for safety and efficiency.

7. Environmental Impact and Sustainability

By optimizing oil change intervals based on actual oil condition, polarization current monitoring can significantly reduce waste oil generation and promote environmentally responsible maintenance practices. The method will assist industries in meeting stricter environmental regulations and sustainability goals.

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