The first report on the BIS project is entitled "Collection and Analysis of Dissolved Gas Analysis (DGA) Data for Ester-based Transformer Fluids and Conclude Method for Interpretation of DGA for Fault Identifications of Ester fluid-filled Transformers (ETD 0108)."

Abstract

Natural and synthetic Ester oils are gaining prominence as an eco-friendly, high-performance alternative to traditional mineral oils in power transformers. Their superior fire safety, biodegradability, and enhanced moisture tolerance make them an ideal choice in modern transformer insulation systems, particularly in environmentally sensitive areas. Ester oils exhibit excellent dielectric properties, superior oxidation stability, and a higher flash point, reducing fire risks and improving transformer safety. Additionally, their ability to absorb and manage moisture better than mineral oils helps extend the life of transformer insulation, leading to increased equipment reliability. This report explores the initial review of ester-based transformer fuels of ester oils over mineral oils, focusing on their environmental benefits, thermal performance, and role in promoting sustainable energy practices. Moreover, it provides an in-depth analysis of relevant international standards which govern the application and testing of ester oils in transformers, ensuring their safe and effective use. Furthermore, the report discusses the economic and technical feasibility of retrofitting existing transformers with ester oils, highlighting case studies where ester oils have enhanced performance and longevity. By addressing both the technical challenges and the benefits of ester oil adoption, this report demonstrates how ester oils contribute to a safer, more sustainable, and reliable electrical grid. With the growing need for greener energy solutions, ester oils represent a forward-looking choice in transformer insulation technology.

Introduction

Dissolved Gas Analysis (DGA) is a critical diagnostic technique extensively used in the electrical power industry to monitor the health and performance of oil-filled equipment, particularly power transformers. As transformers are vital components of electrical grids, ensuring their reliability and longevity is paramount. Over time, transformers are subject to various stresses, including thermal and electrical faults, which can cause the decomposition of insulating materials such as oil and cellulose. This decomposition leads to the formation of gases, which dissolve in the oil.

By analyzing the types and concentrations of these dissolved gases, DGA provides valuable insights into the condition of the transformer, enabling the early detection of potential issues before they escalate into severe failures. The non-invasive nature of DGA, combined with its ability to offer early warning signs of deteriorating conditions, makes it an indispensable tool in the predictive maintenance strategies of utilities and industries worldwide. Through regular DGA, operators can implement timely interventions, thus avoiding costly repairs and unplanned outages and ensuring the continuous and efficient operation of electrical networks. The analysis used several essential standards: IS 6855/IEC 60475-2022, IS 10593/IEC 60599-2022 **and** IS 16589-2023/IEC 61181-2012. These standards provide comprehensive procedures for the sampling, testing, and interpreting of dissolved gases, making them fundamental in the field of transformer diagnostics. By adhering to these standards, professionals can ensure that their DGA results are accurate and reliable, enabling them to make informed decisions regarding transformer maintenance and operation.

Types of Dissolved Gas Analysis (DGA) Methods

(a) Key Gas Method (KGM)

The Key Gas Method is a straightforward approach to Dissolved Gas Analysis (DGA) that focuses on monitoring specific gases known as "key gases," which are closely associated with particular types of transformer faults. These gases include Hydrogen (H_2), Methane (CH_4), Ethylene (C_2H_4), Ethane (C_2H_6), Acetylene (C_2H_2), Carbon Monoxide (CO), and Carbon Dioxide (CO_2). The presence and concentration of these gases help identify whether the transformer is experiencing conditions like overheating, electrical arcing, or insulation degradation. Because it is relatively simple and cost-effective, the Key Gas Method is often used for routine monitoring, quickly indicating potential issues. However, while it is helpful for general diagnostics, it may not always offer the depth of analysis required for complex fault conditions.

(b) Rogers Ratio Method (RRM)

The Rogers Ratio Method is a more detailed DGA technique that uses the ratios of specific gas concentrations to diagnose the type of fault occurring within the transformer. This method analyzes the ratios of Methane to Hydrogen (CH_4/H_2), Ethylene to Ethane (C_2H_4/C_2H_6), and Acetylene to Ethylene (C_2H_2/C_2H_4) to determine whether the fault is due to thermal overheating, electrical discharge, or another issue. Developed by R.L. Rogers, this method is highly regarded in the industry for its accuracy in fault identification, allowing operators to pinpoint specific problems and take appropriate maintenance actions. While it provides a more precise diagnosis than the Key Gas Method, the Rogers Ratio Method requires accurate gas measurements and a deeper understanding of the ratios involved, making it somewhat more complex to interpret.

(c) Duval Triangle Method (DVM)

The Duval Triangle Method is a graphical DGA technique that uses a triangular diagram to diagnose transformer faults based on the relative concentrations of three key gases: Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2). By plotting these gases on a triangular chart, the method visually identifies the type of fault, such as thermal faults, low or high-energy electrical discharges, or partial discharges. The position of the plotted point within the triangle indicates the nature of the fault. This method is particularly appreciated for its simplicity and accuracy in distinguishing between different fault types, making it a popular choice in the industry. However, comprehensive gas data is required to be effective, which can be a limitation if the data is incomplete or inaccurate.

(d) IEC Ratio Method

The IEC Ratio Method, based on standards set by the International Electrotechnical Commission (IEC), utilizes specific gas ratios similar to the Rogers Ratio Method but with standardised interpretations across different regions and manufacturers. This method evaluates the ratios of Methane to Hydrogen (CH_4/H_2), Acetylene to Ethylene (C_2H_2/C_2H_4), and Ethylene to Ethane (C_2H_4/C_2H_6) to diagnose faults such as thermal overheating or electrical discharges. The IEC Ratio Method is widely adopted due to its standardized approach, which ensures consistency and comparability of results across different transformers and environments. While this method is highly reliable, it also requires precise gas measurements and can be complex to interpret, especially for those unfamiliar with the specific ratios and their implications.

(e) Total Combustible Gas (TCG) Method

The Total Combustible Gas (TCG) Method simplifies DGA by measuring the total concentration of all combustible gases in the transformer oil, including Hydrogen, Methane, Ethylene, and Acetylene. This method provides a quick overview of the transformer's condition by indicating the presence of fault conditions that produce combustible gases. The TCG Method is handy as an initial screening tool, indicating whether a transformer is experiencing significant issues. However, while it can signal a problem, it does not differentiate between the types of faults or provide detailed diagnostic information, making it less useful for in-depth fault analysis.

(f) Gas Concentration Trend Analysis

Gas Concentration Trend Analysis involves monitoring the levels of individual gases over time to identify trends that may indicate the development of faults within the transformer. This method doesn't rely on a one-time analysis but instead tracks the changes in gas concentrations such as Hydrogen (H_2), Methane (CH_4), Acetylene (C_2H_2), and others to observe how faults evolve. By analyzing trends, operators can predict potential failures and take preventive action before the fault becomes critical. This method is highly effective for ongoing monitoring and is particularly valuable for critical transformers where early detection of problems is essential. However, frequent or continuous sampling and sophisticated data analysis tools are required to interpret the trends accurately.

(g) Online DGA

Online DGA is a continuous, real-time monitoring approach that uses sensors installed on the transformer to measure the concentrations of dissolved gases in the oil directly. This method provides immediate detection of changes in gas levels, enabling rapid response to developing issues. Online DGA is particularly beneficial for critical transformers where downtime can have significant consequences, such as power generation or transmission networks. The constant monitoring offered by online DGA helps ensure the highest level of operational reliability and safety. However, installing and maintaining online DGA systems can be costly, and they typically focus on key gases rather than providing a complete spectrum analysis.

(h) Off-Line DGA

Off-line DGA refers to the traditional method where oil samples are manually taken from the transformer and analyzed in a laboratory setting. This method is standard for periodic testing and particularly useful during routine maintenance schedules or when online monitoring is unavailable. Off-line DGA provides a comprehensive analysis of the dissolved gases and can use various diagnostic techniques, such as the Key Gas, Rogers Ratio, or Duval Triangle methods. While thorough, the off-line nature means it doesn't provide real-time monitoring, so it may not catch rapidly developing faults between testing intervals. Additionally, the sampling process must be handled carefully to avoid contamination.

(i) Partial Discharge (PD) DGA

Partial Discharge (PD) DGA is a specialized method focused on detecting gases related to partial discharge activities within the transformer. These are early indicators of insulation degradation or other minor faults that could develop into more severe issues. The gases typically monitored include Hydrogen (H_2) and Methane (CH_4), which are produced during partial discharges. This method is crucial for transformers suspected of experiencing partial discharges, as it helps diagnose and address the issue before it leads to significant damage or failure. PD DGA is often used with other diagnostic tools to provide a more complete assessment of transformer health. However, it may not be as effective for diagnosing different types of faults not associated with partial discharges.

1. Analysis of gas in the DGA test

The DGA (Dissolved Gas Analysis) test is a crucial diagnostic tool for assessing the condition of transformers and other oil-filled electrical equipment. One of the critical components of this analysis is the evaluation of gases, particularly gas chromatography analysis of gases such as Hydrogen (H_2), Methane (CH_4), Ethylene (C_2H_4), Acetylene (C_2H_2), and Carbon Monoxide (CO), which can provide insights into the type of fault present in the equipment. The presence of gas concentrations can indicate various issues. For instance, a high level of Hydrogen typically suggests low-energy discharges, such as partial discharge, while elevated levels of Acetylene may indicate arcing or overheating. The standard reference for interpreting DGA results is the IEEE C57.104 guide, which provides fault diagnostic interpretations based on the gas concentrations observed. The ratios of different gases, such as the Duval Triangle or Roger's ratio, are also employed to classify fault types, helping to pinpoint issues like insulation breakdown or overheating. DGA and the analysis of dissolved gases, particularly Hydrogen, serve as critical indicators of transformer health, allowing for early detection and mitigation of potential failures in electrical systems, thereby improving reliability and reducing maintenance costs. Regular monitoring and analysis of these gases are essential to ensure optimal performance and longevity of electrical equipment.

2. Benefits and causes of DGA

Dissolved Gas Analysis (DGA) is an essential diagnostic tool for monitoring and maintaining transformers and other electrical equipment. Here's a detailed overview of the benefits and causes of DGA: Benefits of DGA

(a) Early Fault Detection: DGA helps identify faults such as insulation degradation, overheating, and arcing before they lead to catastrophic failures. This early detection is crucial for preventing unplanned outages and costly repairs.
(b) Improved Reliability: By regularly monitoring the condition of transformers, utilities can enhance system reliability. DGA allows for informed decisions regarding maintenance schedules and the replacement of equipment.
(c) Cost-Effective Maintenance: Regular DGA testing enables predictive maintenance strategies, allowing operators to address issues proactively. This approach can significantly reduce the costs associated with emergency repairs and equipment downtime.
(d) Enhanced Safety: Identifying and addressing potential faults in electrical equipment contributes to a safer working environment, minimizing risks of explosions, fires, or equipment failure that can endanger personnel.
(e) Extended Equipment Lifespan: DGA can contribute to the extended operational life of transformers and other electrical assets by maintaining optimal conditions and addressing issues early.
(f) Informed Asset Management: The data obtained from DGA provides valuable insights for asset management strategies, helping organizations to prioritize investments and allocate resources effectively.

Causes of Gas Generation in Transformers

(a) Thermal Decomposition: Excessive heat can lead to the breakdown of insulating oil and solid insulation materials, generating gases such as Hydrogen, Methane, and Ethylene. This thermal decomposition is often a sign of overheating or failure in insulation.

(b) Electrical Discharges: Partial discharges and arcing within the transformer can produce gases like Acetylene and Hydrogen. These conditions indicate localized high voltages and insulation weaknesses.

(c) Oxidation: The degradation of insulating oil due to oxidation processes can generate gases, including Carbon Dioxide (CO_2) and Carbon Monoxide (CO). High temperatures and moisture content in the oil can accelerate oxidation.

(d) Moisture Presence: Water contamination can facilitate chemical reactions in the transformer oil, leading to the production of gases. Moisture can come from various sources, such as condensation or leaks.

(e) Mechanical Stress: Mechanical faults, such as those caused by vibrations or improper installation, can lead to physical degradation of the insulation and generate gases as a byproduct of the breakdown process.

In conclusion, DGA is an invaluable practice in the management of electrical equipment, providing significant benefits such as early fault detection, cost-effective maintenance, and improved reliability. Understanding the causes of gas generation is crucial for effective monitoring and can guide maintenance strategies to ensure the longevity and safety of transformers and other electrical assets. Regular DGA testing should be integral to the maintenance routine of any electrical system.

Mineral oil

Mineral oil is vital in dissolved gas analysis (DGA) as an insulating and cooling medium for transformers and other oil-filled electrical equipment. It is a highly refined hydrocarbon-based oil chosen for its excellent electrical insulating properties and ability to dissipate heat. Over time, the operational stresses on transformers, such as electrical faults and thermal overloads, cause the degradation of the mineral oil and the solid insulation materials. This degradation leads to the production of various gases, which dissolve in the oil. These dissolved gases—such as Hydrogen, Methane, Ethylene, and Acetylene—provide critical insights into the condition of the transformer, as their concentrations and ratios can reveal the presence of faults like overheating, partial discharges, or arcing. Analyzing these gases through DGA allows for early fault detection, improving transformer reliability and safety. Therefore, mineral oil supports the transformer's function and is a key medium for diagnostic assessments in predictive maintenance strategies.

Mineral oil used in transformers must meet specific standards to ensure its performance as both an insulating and cooling medium and its suitability for use in Dissolved Gas Analysis (DGA). These standards, established by organizations such as the International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), and the Indian Standards (IS), provide guidelines for the quality, testing, and maintenance of mineral oil.

1. IEC Standards

IEC 60296: This standard covers specifications for unused mineral-insulating oils for transformers and switchgear. It outlines mineral oil's properties and performance requirements, such as its electrical strength, breakdown voltage, dielectric dissipation factor, and water content. To ensure reliable operation, the oil must also meet specific oxidation stability and gas absorption characteristics.

IEC 60422: This standard provides guidelines for supervising and maintaining insulating oils in transformers. It details the methods for testing oil quality over time, including detecting moisture, acidity, and dissolved gases that can indicate transformer faults.

2. IEEE Standards

IEEE C57.104: This standard offers guidelines for interpreting dissolved gas analysis of mineral oil in transformers. It provides diagnostic criteria for assessing transformer conditions based on gas concentrations, such as Hydrogen, Methane, and Acetylene, helping to identify thermal and electrical faults in the equipment. It complements the understanding of oil's behaviour under stress and supports the early detection of issues.

IEEE C57.106: This standard specifies the requirements for the acceptance and maintenance of insulating oil in transformers. It includes guidance on the handling, storing, and testing of mineral oil to ensure it retains its electrical and chemical properties throughout its service life.

3. Indian Standards (IS)

IS 335 is the Indian standard for new insulating oil in transformers and switchgear. It defines unused mineral oil's physical, chemical, and electrical properties, such as flash point, viscosity, dielectric strength, and neutralization value. The standard ensures that the oil used in transformers meets the required purity and performance characteristics for adequate insulation and heat dissipation.

IS 1866: This standard provides guidelines for maintaining mineral-insulating oils in equipment. It details methods for the sampling, testing, and reconditioning of in-service oil, ensuring its quality is maintained during the transformer’s operation. It also limits oil parameters like acidity, sludge, and dissolved gases.

Key Parameters in Mineral Oil for DGA:

Gas Absorption Properties: The oil’s ability to dissolve gases is critical for effective DGA. Standards like IEC 60599 and IEEE C57.104 guide interpreting the gases dissolved in oil to diagnose faults.

Oxidation Stability: Standards such as IEC 60296 and IS 335 specify the oil’s oxidation resistance, ensuring it does not degrade quickly, thus maintaining its ability to insulate and cool the transformer.

Water Content: Controlled under standards like IEC 60422 and IEEE C57.106, the water content in mineral oil is vital for preventing electrical breakdown and ensuring dielectric strength

In summary, these IS, IEC, and IEEE standards ensure that the mineral oil used in transformers meets the necessary quality and performance criteria, supporting the reliability of DGA for fault detection and extending the life of electrical equipment.

Graphical Representation of Gas Ratio

The Duval Triangle is a widely used graphical method in Dissolved Gas Analysis (DGA) for diagnosing faults in oil-filled transformers by analyzing the relative concentrations of three key gases: Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2). Developed by Michel Duval, the triangle is divided into different regions, each corresponding to specific types of faults occurring within the transformer. These faults include Partial Discharge (PD), Low-Temperature Thermal Faults (T1), Moderate-Temperature Thermal Faults (T2), High-Temperature Thermal Faults (T3), Low-Energy Discharges (D1), and High-Energy Discharges (D2). A Mixed Fault (D+T) region also indicates thermal and electrical issues.

The concentrations of these gases are plotted within the triangle, with each axis representing one of the gases: CH_4 on the left, C_2H_4 on the right, and C_2H_2 at the bottom. The resulting point inside the triangle indicates the type of fault. For example, points in the D2 region suggest high-energy arcing or discharges, while points in the T3 region indicate high-temperature overheating. The Duval Triangle offers a visual and intuitive approach to diagnosing transformer faults, making it a critical tool for monitoring transformer conditions. It enables operators to quickly determine the nature of internal issues, allowing for timely intervention and maintenance.

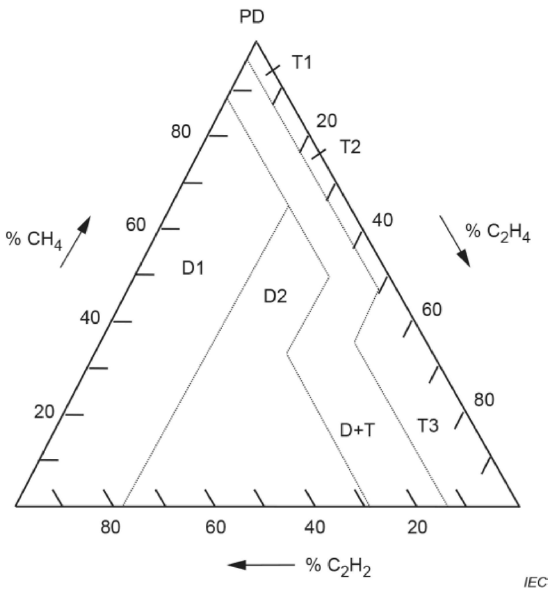

Fig. 1. Duval's Triangle

Ester Oil

Like mineral oil, Ester oil is a dielectric fluid used in transformers for insulation and cooling. However, natural (vegetable-based) and synthetic ester oils have gained attention recently due to their biodegradability, higher flash points, and better moisture tolerance, making them a more environmentally friendly and safe alternative to mineral oils. Ester oils are especially beneficial in transformers operating in ecologically sensitive areas or high-risk locations where fire safety is a concern due to their higher fire point than mineral oil.

Characteristics of Ester Oils:

1. Biodegradability: Ester oils are biodegradable, reducing the environmental impact in case of leaks or spills, which is a significant advantage over traditional mineral oil.

2. High Moisture Tolerance: Ester oils can absorb more moisture without compromising their dielectric properties, helping when transformers are exposed to moisture ingress.

3. High Flash and Fire Points: Their higher flash point makes ester oils less prone to fire hazards, improving the safety aspects of transformer operation.

4. Oxidation Stability: Synthetic ester oils, in particular, offer better oxidation stability than natural esters, which prolong the lifespan of the oil, even in high-temperature conditions.

Standards Governing Ester Oil Usage:

1. IEC 61099 - Specifications for Synthetic Organic Esters for Electrical Purposes:

This standard specifies the properties and test methods for synthetic esters used as transformer insulation oils. It outlines the required parameters such as breakdown voltage, water content, and oxidative stability, ensuring ester oils meet necessary safety and performance criteria. It also provides guidelines for handling, testing, and maintaining the oil during transformer operation.

2. IEC 62770 - "Fluids for Electrotechnical Applications – Unused Natural Esters for Transformers and Similar Electrical Equipment":

This standard deals specifically with natural esters derived from renewable sources, often called vegetable oils, used in transformers. It specifies the composition, properties, and testing methods for natural ester fluids to ensure adequate electrical insulation and cooling under different operating conditions.

3. IEEE C57.147 - "Guide for Acceptance and Maintenance of Natural Ester Insulating Fluids in Transformers":

This standard provides comprehensive guidelines for using, testing, and maintaining natural ester insulating fluids in transformers. It discusses procedures for sampling, testing, and evaluating the performance of natural ester oils throughout their life cycle. The standard also addresses the practical aspects of retro filling mineral oil transformers with ester oils.

4. IS 16081 - "Indian Standard for Natural and Synthetic Ester Oils":

The IS 16081 standard provides the Indian context for using natural and synthetic ester fluids in electrical transformers. It outlines the specifications and testing methodologies specific to ester oils used in the Indian electrical grid, ensuring they meet national performance and safety standards.

Benefits of Ester Oils Over Mineral Oils:

- Fire Safety: Ester oils have a much higher flash point than mineral oils, significantly reducing the risk of fire in transformers and making them suitable for indoor or densely populated areas.

- Environmental Impact: Ester oils are biodegradable, meaning they break down more quickly in the environment, causing less ecological harm in case of spills or leaks.

- Moisture Management: Ester oils can absorb and hold moisture better than mineral oils without losing dielectric strength, improving transformers' longevity and reliability, especially in humid environments.

Conclusion

Ester oils provide a sustainable and safe alternative to mineral oils in transformers, particularly in applications requiring high fire safety or environmental protection. Standards like IEC 61099, IEC 62770, IEEE C57.147, and IS 16081 ensure that ester oils meet stringent performance and safety criteria, making them viable for modern transformer insulation and cooling solutions. These standards also guide the testing, acceptance, and maintenance processes, ensuring the longevity and efficiency of ester oil-filled transformers.

Till date, DGA report of ester oil was requested from utility and manufacturing companies by the PI and BIS authorities. So far, no data has been received.

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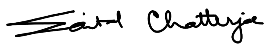 26/09/24

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