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Early Fault Detection and Leveraging Dissolved Gas Analysis for Proactive Life Management of Power Transformers.

(Case Study of Yola Electric Distribution Company)

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Abstract

Power transformers are critical components for ensuring the reliability and efficient operation of electrical power systems. This paper presents a comprehensive review of fault detection techniques in power transformers, with a particular focus on the application of Dissolved Gas Analysis (DGA) for proactive life-cycle management. Timely maintenance, guided by the identification of incipient faults or signs of insulation deterioration is essential to preserving transformer integrity and achieving long-term system reliability. The review critically examines the advantages and limitations of various fault detection and diagnostic methodologies. Notably, even under normal operating conditions, transformers in prolonged service gradually produce characteristic gases due to aging and thermal stress. This study further outlines a systematic approach to fault detection and condition assessment through DGA, offering a framework for the proactive management of transformer lifespan and asset performance.

KEYWORDS: Transformer, Dissolve Gas Analysis DGA, Fault,

1. INTRODUCTION

High-power electrical equipment plays a pivotal role in the reliable operation of power distribution and transmission systems. Among these assets, power transformers are particularly critical: their failure can trigger cascading outages and result in widespread, catastrophic power disruptions. Zheng et al., (2022). As noted by Huang and Sun, power transformers represent some of the most capital-intensive components in electrical infrastructure. They are susceptible to irreversible internal damage due to combined electrical, mechanical, and thermal stresses, even during normal operation. Consequently, robust techniques for early fault detection and prognosis are essential to ensure system resilience and operational continuity (khalil,2018). Moreover, maintaining transformer reliability is not only vital for grid stability but also key to achieving cost-effective power transmission. K. Spurgeon. et al., (2013). To mitigate the risk of catastrophic failures, it is essential to implement an effective condition monitoring system capable of providing early warnings of incipient fault conditions. Such systems rely on close and continuous surveillance of critical transformer parameters. Insulating oil plays a central role in this context: owing to its excellent dielectric properties, it enhances the integrity of the transformer's insulation system. For optimal performance, the oil must exhibit high dielectric strength and a low dissipation factor to effectively withstand operational electrical stresses.

Dissolved Gas Analysis (DGA) is a widely recognized and indispensable diagnostic tool for assessing transformer health. Liang et al., (2018). During abnormal thermal or electrical events, the decomposition of insulating oil and solid insulation materials generates characteristic gases. DGA entails the quantitative and qualitative analysis of these dissolved gases, offering critical insights into the nature, severity, and progression of internal faults. A. Abu-Siada (2015). Different fault types such as partial discharge, overheating, or arcing produce distinct gas composition patterns. These signatures can be reliably detected and interpreted using analytical techniques such as gas chromatography, enabling timely and informed maintenance decisions.

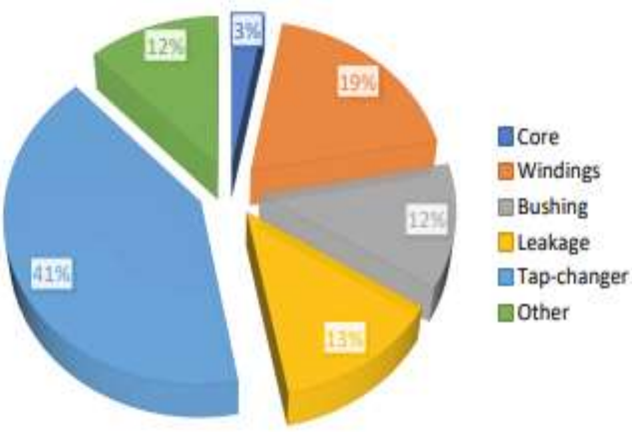


Figure:1 Percentage of causes of failure of power transformers (CIGRE survey), Khalil (2018).

Transformer failures can be broadly classified into electrical, thermal, mechanical, or environmental categories. As reported by Khalil (2018). Studies conducted under the auspices of the Conseil International des Grands Réseaux Électriques (CIGRÉ) indicate that approximately 40% of power transformer failures originate in the tap changer mechanism. Failures in internal core components, such as the magnetic core and windings account for about 3% of cases, while the remainder occur in ancillary elements including bushings, tanks (or bins), and other accessories, as illustrated in Figure 1.

2.0 LITERATRE REVIEW

The reliable operation of power transformers is paramount to the stability and efficiency of modern electrical power systems. In response to this critical need, recent research has proposed fast and lightweight fault diagnosis frameworks to enhance real-time monitoring capabilities. Ali, Ms et al (2023). Among established diagnostic techniques, the analysis of gases dissolved in insulating oil commonly known as Dissolved Gas

Analysis (DGA) has proven highly effective for detecting incipient faults in oil-immersed power transformers during service. As highlighted in the preceding literature review, however, relatively few studies have integrated machine learning algorithms with fuzzy logic systems to predict or prevent transformer failures by leveraging DGA-derived gas patterns. This is notable given the demonstrated success of both methodologies in related diagnostic and prognostic applications. A. Emsley (1994). These critical assets are often subjected to significant electrical, thermal, and mechanical stresses throughout their operational lifespan. Condition monitoring and timely maintenance are crucial to prevent catastrophic failures, minimize downtime, and optimize asset utilization. M. Duval (2003). Among the various diagnostic techniques employed, Dissolved Gas Analysis (DGA) has emerged as a powerful and widely accepted method for assessing the internal condition and predicting the remaining useful life of power transformers (IEEE Std C57.104-2019). Power transformers are complex electromechanical devices susceptible to various degradation mechanisms. These include thermal degradation of insulating materials (primarily paper and oil), partial discharges, arcing, and overheating of windings or core components (CIGRE Brochure 343, 2008). Different types of internal faults in power transformers produce characteristic hydrocarbon and non-hydrocarbon gases that dissolve in the insulating oil. The identity and concentration of these dissolved gases offer critical diagnostic information regarding the nature, type, and severity of incipient faults. Kori et al., (2012). Dissolved Gas Analysis (DGA) entails the extraction and quantitative measurement of these gases from transformer oil samples. The underlying principle of DGA articulated by Duval (2002) is that each fault mechanism generates a distinct gaseous "fingerprint." Key diagnostic gases include hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2). By analyzing their individual concentrations and relative ratios, engineers can infer the likely fault type (e.g., partial discharge, thermal overheating, or arcing). For instance, elevated levels of acetylene (C_2H_2) are strongly indicative of high-energy arcing faults. Bangalore, P et al., (015). To support consistent interpretation, several standardized methods and guidelines such as the Duval Triangle, IEC 60599, and IEEE C57.104 have been developed. These frameworks systematically correlate gas patterns with specific failure modes, enabling more accurate and reliable condition assessment of power transformers. These methods utilize the ratios of specific gas concentrations to categorize fault types into distinct zones or codes. These methods have been widely adopted due to their simplicity and effectiveness in many cases. Christina, A. et al., (2018). Another set of gas ratios used for fault diagnosis. While established methods have proven valuable, ongoing research focuses on enhancing the accuracy and predictive capabilities of DGA. Some key areas of advancement include: Development of more sensitive and reliable gas chromatography methods and online DGA monitoring systems. De Almeida Pais, et ai., (2021). Utilizing large datasets of DGA results and transformer operational data to develop more sophisticated diagnostic models and predictive algorithms. Daurenbayeva, et al., (2023). Machine learning techniques can identify complex patterns and correlations that may not be apparent through traditional ratio methods.

A more comprehensive assessment of transformer health can be achieved by integrating Dissolved Gas Analysis (DGA) with complementary condition monitoring techniques, such as vibration analysis, infrared thermography, and oil quality testing Arena, F et al., (2022). Although not a DGA method per se, the analysis of furanic compounds in transformer oil provides valuable insights into the degradation state of cellulosic (solid) insulation. Consequently, furan analysis is frequently employed alongside DGA to support a more holistic evaluation of transformer aging and remaining useful life. Hazra, J et al., (2009). Despite the emergence of advanced monitoring technologies, DGA remains an indispensable diagnostic tool for evaluating transformer condition and forecasting operational lifespan. This literature review has outlined the foundational principles of DGA, established interpretation methodologies (e.g., IEC 60599, IEEE C57.104, and Duval diagrams), recent technological advancements, and persistent challenges in fault identification and data interpretation. Future research focused on multi-sensor data fusion frameworks which synergistically combine DGA with heterogeneous data streams from thermal, mechanical, and chemical sensors holds significant promise for enhancing the accuracy, robustness, and predictive capability of transformer health assessment. Such integrated approaches could enable real-time, intelligent diagnostics and substantially improve the reliability and efficiency of modern power systems.

3.0 METHODOLOGY

This study investigates and comparatively evaluates seven widely used dissolved gas analysis (DGA)-based methods for diagnosing incipient faults in power transformers: The Key Gas Method, Dornenburg Ratio Method, Rogers Ratio Method, Nomograph Method, IEC Ratio Method, Duval Triangle Method, and CIGRÉ Method. Among condition monitoring techniques, DGA is particularly advantageous for online fault diagnosis, as it does not require the transformer to be taken out of service. To enhance diagnostic accuracy, a fuzzy logic system was developed to classify transformer faults based on DGA data, adhering to the guidelines of the IEC 60599 standard. This system employs membership functions tailored to the statistical and physical characteristics of the input gas dataset. Logical operators such as AND and OR are used to aggregate the degrees of membership across key diagnostic gases, enabling nuanced fault classification even in the presence of ambiguous or overlapping gas patterns. Effective implementation of DGA relies on routine oil sampling and, increasingly, on modern online gas monitoring technologies. A critical step in the diagnostic process is the accurate interpretation of the fault type responsible for the observed gas generation. Under abnormal electrical or thermal stress, the insulating oil and solid cellulose materials decompose, releasing trace amounts of characteristic gases whose type and concentration serve as primary indicators of the underlying fault mechanism.

The composition of gases generated in oil-filled power transformers is closely correlated with the type and severity of the underlying fault. The detection of elevated concentrations of specific gases during routine monitoring often serves as the earliest indicator of an incipient malfunction—potentially preventing catastrophic failure if addressed promptly. Common mechanisms of gas generation include high-energy arcing, partial discharge (corona), low-energy sparking, thermal overheating due to severe overloading, and failure of forced cooling systems. Different fault conditions produce characteristic gaseous byproducts, with the predominant gases varying according to fault energy and temperature. The primary diagnostic gases include hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2). Most of these gases are combustible, and their presence reflects the decomposition of mineral oil and/or cellulosic insulation under electrical or thermal stress. An increase in Total Combustible Gases (TCG), particularly when accompanied by a rising rate of gas generation, may signal the presence of one or a combination of fault types thermal, electrical, or corona-related. To interpret these gas patterns and assess transformer health, utilities and standards organizations have adopted various DGA-based diagnostic methods, each offering distinct approaches to fault identification and severity classification.

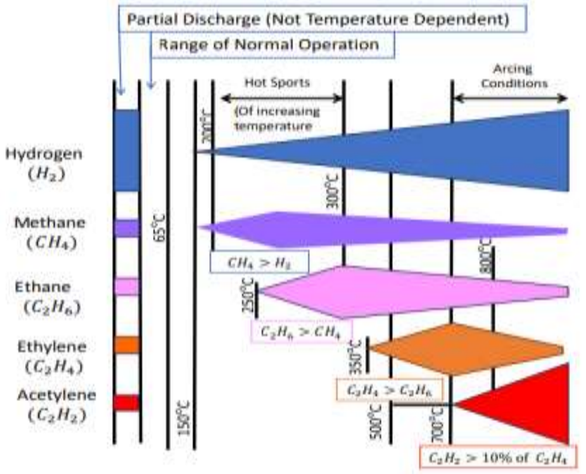


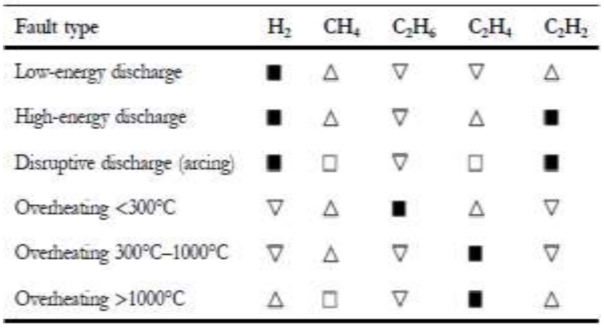
Figure 2: Comparative oil gas evolution rates as a function of decomposition energy; adapted from. Golarz, J. (2016) & Bangalore, P et al., (2015).

3.1 Dissolved Gas Analysis fault detection Procedure

The Dissolved Gas Analysis (DGA) procedure involves three principal steps: (1) oil sampling from the transformer, (2) extraction of dissolved gases from the oil, and (3) quantitative and qualitative analysis of the extracted gas mixture, typically performed using gas chromatography (GC). Following extraction, the gas mixture is introduced into adsorption columns within the GC system, where individual gas components are separated based on their differential affinities for the column's stationary phase. As a result, each gas elutes at a distinct retention time and is subsequently detected by a suitable sensor (e.g., thermal conductivity or flame ionization detector).

This process enables the separation, identification, and quantification of individual gaseous constituents. Gas concentrations are commonly reported in parts per million by volume (ppm), expressed as the volume of gas at standard temperature and pressure (STP) per unit volume of oil (i.e., µL gas/L oil or ppm v/v). The relative composition of key diagnostic gases provides critical insights into the nature of internal faults. For instance, the presence of hydrogen (H_2) is strongly associated with partial discharges (PD), while elevated acetylene (C_2H_2) typically indicates high-energy arcing. Thus, accurate interpretation of DGA results forms the cornerstone of effective transformer condition monitoring and predictive maintenance strategies

3.1.1 Table 1. Relationship between the key gases and fault type according to



Fault type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Low-energy discharge	■	△	▽	▽	△
High-energy discharge	■	△	▽	△	■
Disruptive discharge (arcing)	■	□	▽	□	■
Overheating <300°C	▽	△	■	△	▽
Overheating 300°C–1000°C	▽	△	▽	■	▽
Overheating >1000°C	△	□	▽	■	△

■ Key gas for the respective fault type.
□ Secondary characteristic gas (high concentration).
△ Secondary characteristic gas (low concentration).
▽ Gas not typical for the respective fault type.

Power transformers, or simply transformers, according to Li, et al., (2022), have the highest equipment value in a power system, representing up to 60% of the total investment. According to author in Liang, et al., (2018), the technical performance is driving most utilities to continuously assess the actual health of their transformers. Transformers and high-voltage cables are insulated with a combination of cellulose paper and insulating mineral oil that provides 40 years of reliability.

3.2 Overview of Power Transformer Failures

Power transformers are susceptible to a range of failure modes, many of which can be mitigated through robust and proactive maintenance strategies. T. Suwanasri et el., (2008)

3.2.1. Power Transformers

Power transformers often referred to simply as transformers are among the most critical and capital-intensive assets in electrical power systems. According to Li, et al., (2022), they account for up to 60% of the total investment in transmission infrastructure, underscoring their economic significance. As noted in Li, et al. (2020). The growing emphasis on grid reliability and asset longevity has driven utilities to continuously monitor and evaluate the real-time health condition of their transformer fleets. The insulation system in oil-filled power transformers typically consists of a synergistic combination of cellulose-based paper and mineral insulating oil, which together are engineered to provide reliable service for approximately 40 years under normal operating conditions. The cellulose paper is composed of roughly 90% cellulose, 6–7% hemicellulose, and 3–4% lignin. Hamed, et al., (2020). Cellulose a natural polymer of glucose undergoes gradual depolymerization during service due to thermal, electrical, and oxidative stresses. This degradation process breaks the polymer chains, releasing byproducts such as water, acids, and furanic compounds into the insulating oil, which serve as key indicators of solid insulation aging. Huang et al., (2013).

3.2.2. Typical Failures and Maintenance Methods

To ensure the continued suitability of insulating oil for service in power transformers, its key physicochemical and dielectric properties are routinely evaluated against the acceptance criteria specified by transformer manufacturers, utility operators, and oil refiners. Martinset al., (2023). Upon filling, the cellulose-based insulation paper being inherently hygroscopic absorbs moisture from the oil. This moisture uptake significantly compromises the dielectric strength of the solid insulation and accelerates aging, thereby reducing the transformer's expected service life. Fofana, I (2010). Consequently, regular and systematic inspection of power transformers is essential to detect incipient faults at an early stage and mitigate further degradation before it leads to failure. Fu,X et al., (2022). In this context, standardized maintenance protocols have been developed to guide condition assessment and intervention strategies. For instance, a comprehensive flowchart outlining the recommended transformer maintenance procedure has been published and is presented in Figure 3. Furthermore, significant efforts have been dedicated to analyzing the root causes of power transformer failures to inform preventive and predictive maintenance practices. M. Duval (2003).

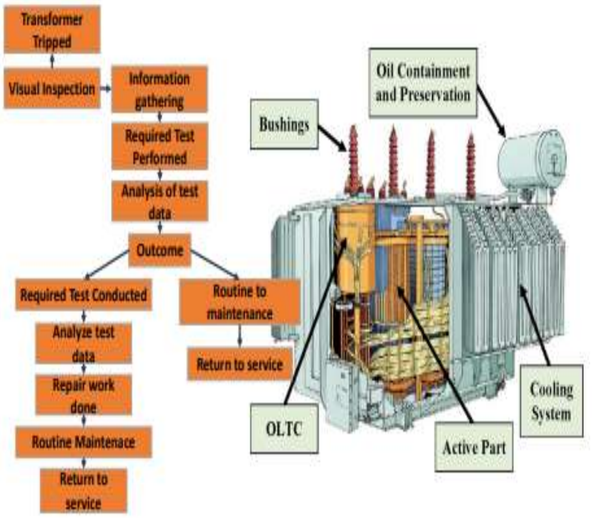


Figure 3: Flowchart / part of power transformer maintenance. Hamed, et al., (2020).

Figure 4: Detecting fault for proper repair in 33KVA power transformer

When a power transformer fails, the utility is typically faced with two costly options: repair or full replacement both of which entail significantly higher expenses and operational disruption compared to routine or predictive maintenance. Early detection of developing faults, before they escalate into catastrophic failures, is therefore critical to avoiding unplanned outages and minimizing transmission or distribution downtime. Implementing predictive maintenance strategies enables utilities to proactively address anomalies, substantially reducing the risk of failure and ensuring continuity of service. Khalid (2018) &Hamed (20200). As illustrated in the figure above, the Yola Distribution Company carries out transformer repair operations in the Geidam Local Government Area (LGA), demonstrating practical efforts to restore failed units and maintain grid resilience at the distribution level.

Figure:5 Types of maintenance policie**s.**

Figure 6: Corrective maintenance of 33KVA power transformer

Research efforts have increasingly focused on evaluating and integrating diverse methodologies for the life-cycle management of power transformers. These approaches encompass a wide range of diagnostic and monitoring techniques, including Frequency Response Analysis (FRA), voltage recovery assessments, infrared thermal imaging, tap changer performance testing, bushing diagnostics, and continuous or periodic monitoring of key parameters such as dissolved gas concentrations, oil and winding conductor temperatures, moisture content, and oil quality indicators (e.g., dielectric strength, acidity, color, and interfacial tension). Additionally, partial discharge (PD) measurements are widely employed to detect early-stage insulation degradation and localized electrical faults. Sheetz (2002).

3.3 Working Principle

Transformer failure detection data were employed to train and evaluate several fault prediction models, including artificial neural networks (ANNs), support vector machines (SVMs), decision trees, and fuzzy logic systems. The results obtained from these models are presented and critically discussed in terms of accuracy, robustness, and interpretability. A cornerstone of the diagnostic input for these models is Dissolved Gas Analysis (DGA), a widely accepted method for detecting incipient faults in oil-immersed power transformers. DGA enables fault characterization by analyzing the concentrations of key gases, such as hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2) dissolved in the transformer oil. Each fault type (e.g., partial discharge, thermal overheating, or arcing) produces a distinct gaseous signature, which is captured in the dataset used for model development. This dataset includes labeled DGA samples corresponding to known fault conditions, thereby facilitating supervised learning and enabling reliable fault classification.

4.0 RESULT AND DISCUSSION

This research presents a strategic leveraging of Dissolved Gas Analysis (DGA) for the proactive life-cycle management of power transformers, with the overarching goals of enhancing system reliability, minimizing unplanned downtime, and extending equipment service life. By detecting early indicators of internal faults and insulation degradation, DGA facilitates timely and informed maintenance decisions. As a well-established diagnostic technique for oil-immersed transformers, DGA enables condition-based and predictive maintenance strategies, thereby reducing the risk of catastrophic failures and optimizing maintenance scheduling. The findings of this study demonstrate that the systematic application of DGA, particularly when integrated with intelligent diagnostic models leads to measurable improvements in transformer reliability, significant reductions in maintenance and replacement costs, and a demonstrable extension of operational lifespan. Collectively, these benefits contribute to greater operational efficiency and substantial cost savings for power utilities and industrial operators.

5.0 CONCLUSIONS

Several diagnostic techniques for fault detection in power transformers are based on the analysis of gases dissolved in the insulating oil, a method commonly known as Dissolved Gas Analysis (DGA). According to the IEEE Standard C57.104, DGA enables the identification of a coded set of fault types, including partial discharge (PD), low-energy discharges (D1), high-energy discharges (D2), thermal faults at low and high temperatures, and combinations thereof. Effective power transformer asset management is of paramount importance, as the reliable operation of these critical assets directly impacts grid stability, economic efficiency, and societal well-being. In this context, structured maintenance strategies, particularly preventive and predictive maintenance facilitate early and accurate diagnosis of incipient faults, allowing timely interventions before catastrophic failure occurs.

This study demonstrates that both Fuzzy Logic (FL) and Multilayer Perceptron (MLP) classifiers achieve high diagnostic accuracy when applied to a balanced DGA dataset in which all fault classes are optimally represented. Specifically, the models attained classification accuracies of 96% for partial discharge (PD), 95% for low-energy discharges (D1), and 58% for high-energy discharges (D2). While these results are promising, the limited size of the current dataset constrains model generalizability. Future work will explore alternative classifier architectures and, crucially, expand the training dataset to enhance model robustness, improve performance—particularly for underrepresented fault types such as D2—and increase confidence in real-world deployment scenarios

6. RECOMMENDATIONS

Authors are advised to adhere with the guidelines of this document in order for their article to get published.

7. ACKNOWLEDGEMENT (if any)

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