Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Comparative DGA-Based Fault Diagnosis and Root-Cause Assessment of Transformer using Duval Triangle and Pentagon Graphical Method

Varsha Thakur

vthakur.phd2024.ee@nitrr.ac.in

National Institute of Technology Raipur

Chilaka Ranga

National Institute of Technology Raipur

Research Article

Keywords: Transformer, DGA real-dataset, Fault diagnosis, graphical approach Duval pentagon

Posted Date: November 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10915328/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Comparative DGA-Based Fault Diagnosis and Root-Cause Assessment of Transformer using Duval Triangle and Pentagon Graphical Method

Varsha Thakur, Chilaka Ranga

vthakur.phd2024.ee@nitrr.ac.in, and *cranga.ee@nitrr.ac.in*

Abstract

Power transformers are essential components of modern electrical power systems, and insulation degradation is one of the major contributors to transformer failure. This study presents a comparative root-cause assessment with DGA-based fault diagnosis, and insulation condition evaluation of real power transformers using the Duval Triangle and Duval Pentagon techniques. Dissolved Gas Analysis (DGA) has emerged as one of the most widely used techniques for diagnosing incipient faults in oil-filled transformers. Various DGA interpretation methods, including Rogers Ratio, IEC 60599, and Duval Triangle, have been extensively applied for fault identification. However, ratio- based techniques often suffer from diagnostic ambiguity due to overlapping fault boundaries. This paper presents a fault-based root cause of a failed power transformer using DGA diagnostic techniques. The study is based on real DGA data obtained from transformer oil sample collected after a transformer failure that occurred during the hot-climates at the high temperature, analyze internal fault mechanisms, various incipient fault classification were evaluated. Oil samples were investigated using various diagnostic techniques such as DRM, RRM and IEC 60599 standard, and the obtained results were compared with those derived from the Duval Triangle Method. The analysis revealed the presence of both electrical and thermal fault signatures in the oil samples, indicating severe deterioration of the internal insulation system.The results confirm the effectiveness of DGA for post-failure transformer diagnostics. DTM for accurate fault identification, condition assessment, and maintenance planning in power transformers. Hence, focus on advanced graphical methods for improving the effectiveness and efficiency of fault identification

Keywords Transformer, DGA real-dataset, Fault diagnosis, graphical approach Duval pentagon.

Introduction

Oil-Filled transformer are widely used in electrical power systems. The insulation oil along with cellulose insulations determines transformer lifespan and reliability. Oil degradation can ultimately lead to transformer failure. Such failures disrupt power supply and cause economic losses. Additionally, oil degradation reduces the service life of the transformer[1]. Transformer insulation mostly consists of hydrocarbon oil and cellulose-based paper. The insulation of many power transformers used in electrical utilities worldwide is rapidly reaching a degradation state due to severe thermal effects[2-3]. Transformer failure can lead to substantial economic losses and prolonged power supply interruptions Therefore effective condition monitoring and fault diagnosis are essential for ensuring operational reliability and enabling predictive maintenance planning. Continuous monitoring of liquid and solid insulation in power transformers enables early detection of insulation deterioration and abnormal operating conditions. Effective condition monitoring significantly reduces transformer failure risk by supporting timely preventive and corrective maintenance actions based on real-time health assessment. As a results, it enhances operational reliability and extends the service life of the transformer []. Although several DGA-based diagnostic methods have been developed for transformer fault identification, the reliability of ratio-based methods is often affected by overlapping fault boundaries and inconsistent interpretations under similar operating conditions [1-5].To address this challenge, this paper presents a comprehensive comparative analysis of the Duval triangle, IEC 60599, and Roger Ratio methods using transformer oil sample data. The study investigates the capability of these techniques to accurately distinguish between high -temperature thermal faults (T3), high-energy discharge (D2), and low- energy discharge (D1). The obtained results highlight the effectiveness of the Duval Triangle in providing clearer fault-zone separation and reduced diagnostic uncertainty[6-7]. Although several DGA-based diagnostic methods have been developed for transformer fault identification, the reliability of ratio-based methods is often affected by overlapping fault boundaries and inconsistent interpretations under similar operating conditions []. To address this challenge, this paper presents a comprehensive comparative analysis of the Duval triangle, IEC 60599, and Roger Ratio methods using transformer oil sample data. The study investigates the capability of these techniques to accurately distinguish between high -temperature thermal faults (T3), high-energy discharge (D2), and low- energy discharge (D1). The obtained results highlight the effectiveness of the Duval Triangle in providing clearer fault-zone separation and reduced diagnostic uncertainty

Transformer Aging and Failure

Transformers aging and failure are primarily governed by the degradation of liquid and solid insulation system under continuous operational system. High temperature or overheating, caused by overheating or inadequate cooling, accelerates electrical, thermal, and chemical stress within the transformer [4-7]. Electrical stress arising from high electrical electric

fields and partial discharges, thermal stress due to sustained elevated temperature, and chemical stress from oxidation and contamination collectively initiate the deterioration of oil and paper insulation. Oxidation of the insulation of oil and cellulose paper results in the formation of acidic compounds, sludge, and increased moisture content [10]. These degradation by products reduce heat transfer efficiency and significantly lower the dielectric strength of the oil-paper insulation system [11]. As dielectric strength decreases, the risk of insulation breakdown increases, leading to insulation failure and unsafe operating conditions. Ultimately, such failures result in transformer outages, increased operational risk, economic losses, and a substantial reduction in the service life of power transformers.

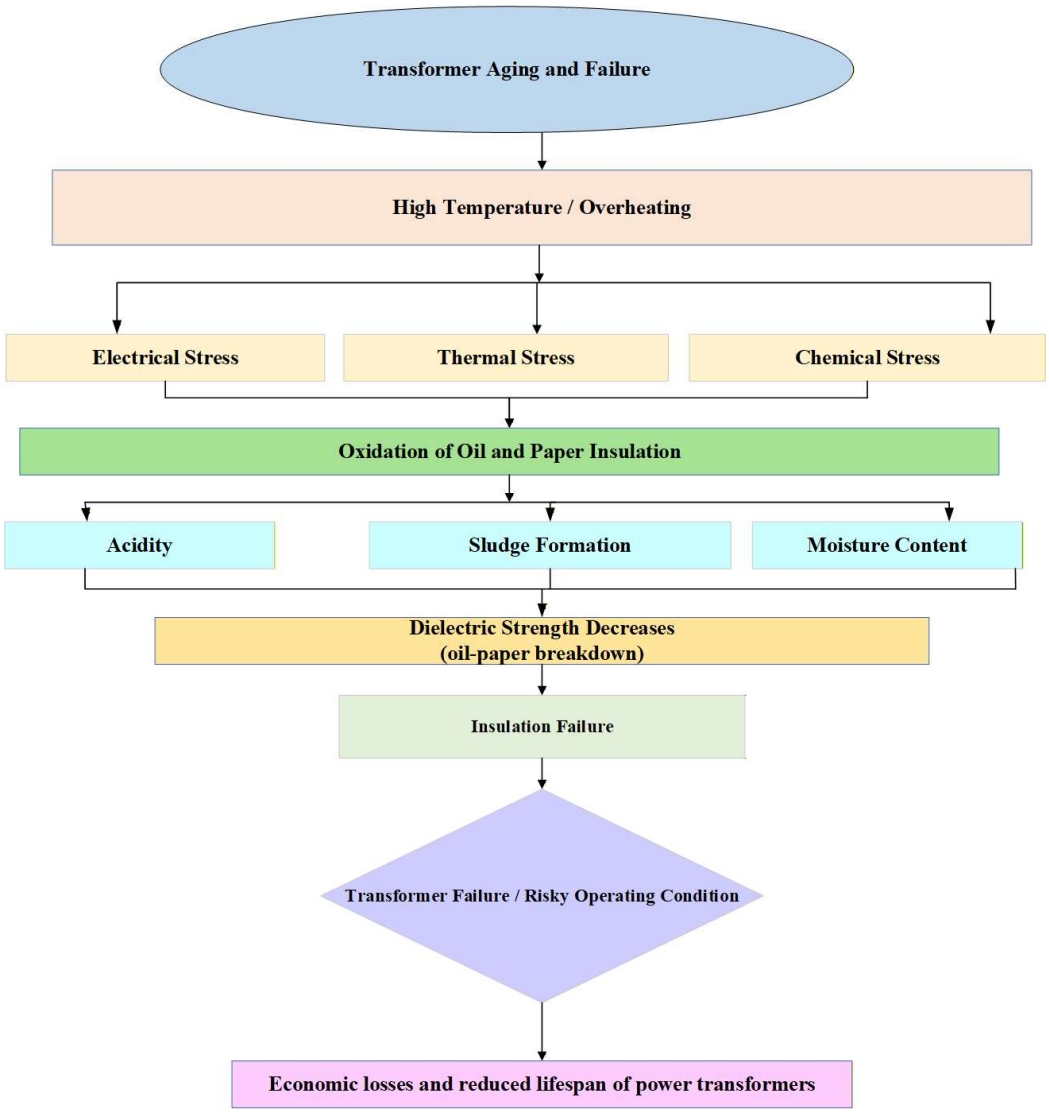


Figure:1 Transformer aging progression and failure flow chart

Transformer design involves high-quality, cooling systems, and robust mechanical, insulation complex materials structures to withstand electrical, chemical, thermal, and environmental stresses. Power system reliability and continuous operation are significantly affected by transformer failures. Power transformers are continuously increasing thermal. chemical, electrical, and mechanical stresses due to rising energy losses, insulation damage system overloading, and severe operating conditions [Over time, these stresses can cause high oxidation and high breakdown of insulation systems, leading to reduced dielectric strength, overheating, and insulation breakdown 12,13]. Therefore, ensuring the reliability and longevity of power transformers is a major concern for power utilities.

Effective condition monitoring, proper insulation systems, and the use of reliable insulation materials oilpaper are essential to minimize failure risks and enhance transformer continuous performance [14]. Improving transformer reliability not only ensures uninterrupted power supply but also supports the overall efficiency and sustainability of modern power systems. A biodegradable, eco-friendly, and high fire point ester oil is recommended as an alternative (plant based) insulating fluid to minimize the risk of failures [15].

Multi-Gas DGA Interpretation for Transformer Fault Diagnosis

Dissolved Gas Analysis (DGA)

Transformers utilize hydrocarbon-based petroleum mineral oil to provide both electrical insulation and heat dissipation. So this oil decomposes and produces various gases. Different types of gases are released during transformer oil and insulation decomposition, and each gas indicates specifics type of fault. For instance (CO and CO_2) are mainly associated with cellulose degradation of paper insulation [16-17]. Hydrocarbon gases such as Hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene(C_2H_4), and acetylene (C_2H_2) are mainly related to thermal and electrical faults in liquid insulation. Gas generation occurs due to thermal and electrical stress at different temperature levels inside the transformers.

Doernenburg Ratio Technique for fault Diagnosis

The Doernenburg Ratio Method, developed in 1970, is a dissolved gas analysis (DGA) technique used for transformer fault diagnosis. It identifies faults such as arcing, thermal and corona discharge by analyzing key gas concentration ratios including R1=CH_4/H_2, R2 = C_2H_2/ C_2H_4, R3= C_2H_2/ CH_4, R4= C_2H_6/ C_2H_2 [7,10,16]. This method operates on thermal deterioration and used gas concentration ratio beyond threshold limits to classify transformer faults into PD, overheating, electrical arcing and thermal faults. This method has several limitations [18] It is applicable only when gas concentrations exceed predefined threshold limits otherwise results may be inconsistent. It employs limited gas ratios, leading to incomplete fault representation, reduced effectiveness in complex fault detection, and dependence on fixed ratio thresholds that may not suit all operating conditions.

Table 1. Fault diagnosis by DRM

Fault Diagnosis	**R1**	**R2**	**R3**	**R4**
Thermal Decomposition	>1.0	<0.75	<0.3	>0.4
Corona (low intensity PD)	<0.1	Insignificant	<0.3	>0.4
Arcing (high intensity PD)	>1.0 <0.1	>0.75	>0.3	<0.4

Roger's Ratio-based Technique for fault Classification

Roger's ratio method is a DGA technique used for transformer fault diagnosis. The ratio technique in DGA helps detect early transformer faults, reducing breakdowns and repair costs[7]. This technique is based on a gas-ratio classification approach used to identify various transformer fault conditions such as normal conditions, electrical energy discharge, and thermal faults, and it is accepted as an IEC standard method. It utilize dissolved gas analysis of transformer oil based on five gases CH_4, C_2H_6, C_2H_4, C_2H_2, and H_2 to form three ratios R1, R2, R3 for fault identification. R1 = CH_4/ H_2 indicates low-temperature thermal or partial discharge, R2 = electrical discharge or arcing, and R3 = C_2H_4/ C_2H_6 indicates thermal fault severity. This method shows that acetylene is mainly produced in electrical discharge faults, reflects thermal fault severity and temperature rise in the transformer [10-16]. These ratios classify condition into normal, partial discharge, electrical arcing, and thermal fault. In practical operation, multiple gases are generated simultaneously, causing overlapping ratio values and reducing the accuracy of ratio-based diagnosis.

Table 2. Roger Ratio (RRM) [7,16]

Fault Type	**R1**	**R_2**	**R_3**	**Case**
Normal	<0.1	0.1 to 1.0	<1.0	0
Low energy density arcing (PD)	<0.1	<0.1	<0.1	1
High energy discharge (Arcing)	0.1 to 3.0	0.1 to 1.0	>3.0	2

Thermal (Low Temperature)	<0.1	0.1 to 1.0	1.0 to 3.0	3
Thermal<700°C	<0.1	>1.0	1.0 to 3.0	4
Thermal>700°C	< 0.1	>1.0	>3.0	5

Proposed Methodology Graphical Approaches

Transformer oil sample collection

In this study, real-time Dissolved Gas analysis (DGA) data obtained from failed power transformers of the Chhattisgarh State Electricity Board (CSEB) is utilized for fault diagnosis and performance evaluation. The transformers selected for analysis are operating under hot climatic conditions, where high ambient temperatures significantly accelerated the thermal aging of transformer oil and paper insulation. The failure cases considered in this work are associated with operational transformers that experienced abnormal gas generation due thermal stress, overloading, and insulation degradation. The DGA data includes key hydrocarbon gases such as Acetylene C_2H_2, C_2H_4, and CH_4, which are primary indicators of internal transformer faults. Due to the severe environmental conditions especially during peak summer months, the transformer insulation system undergoes rapid deterioration. This leads to increased gas formation inside liquid dielectric, which is captured through laboratory-based DGA testing [11,16] The collected gas concentrations are further employed for fault classification using diagnostic techniques such as the Duval Triangle Method. The real failure data obtained from utility transformers provides a practical and realistic basis for analysis, enabling accurate fault and fault zone identification of electrical discharge faults (PD, D1, and D2) and thermal faults (T1-T3). This method facilitates the acquisition of empirically derived data under actual operating conditions, thereby improving the accuracy, reliability, and practical applicability of the diagnostic results.

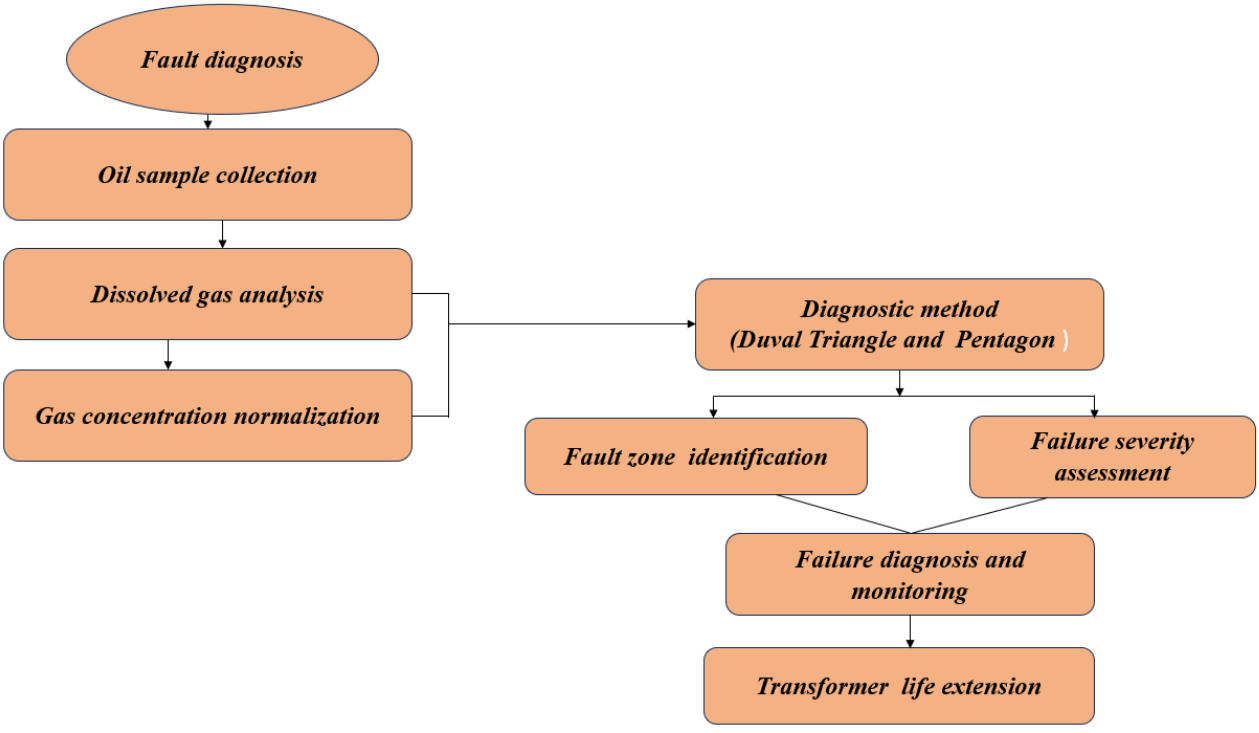


Fig. 2 Flowchart for transformer fault diagnosis using Duval Triangle and Pentagon Method Analysis

Duval Triangle-Based Three-Gas Fault Diagnosis

The investigation methodology involves a detailed analysis of a failed power transformer using DGA. In this study, the Duval Triangle (DTM) diagnostic and Duval Pentagon graphical approach technique was employed to identify the type of fault and determine the corresponding fault zone within the transformer[18,19]. Based on the concentration ratios key dissolved gases, the fault condition was interpreted and classified into specific electrical and thermal fault regions. This

analysis provides a comprehensive understanding of the fault characteristics and the extent of insulation degradation within the transformer, thereby enhancing the effectiveness and precision of transformer fault diagnosis.

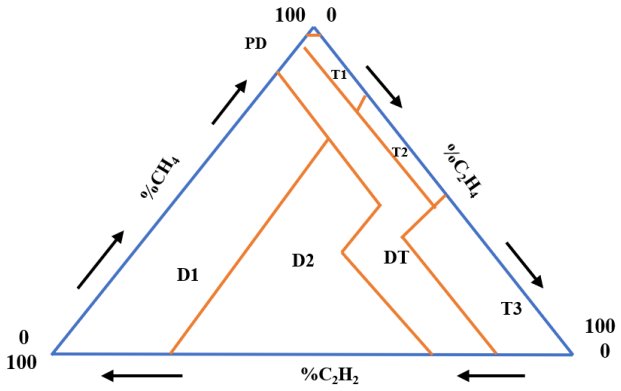


Fig. 3 Duval triangle for transformer fault diagnosis [16]

This method accepted due to its clear fault classification capability. The IEEE Std C57.104 fault classification table defines the diagnostic fault zone of the DTM using the percentage concentrations of gases acetylene, ethylene, and methane gases obtained from DGA. The classifies transformer faults such as partial discharge and electrical discharge faults (D1, D2, and DT) based on characteristic gas concentration ranges, enabling accurate and reliable transformer fault diagnosis Duval triangle method uses gas percentages instead of absolute concentrations to provide a normalized and more reliable for transformer fault interpretation

Table 3. Duval Triangle gas percentages and fault description [16]

Fault Gas%	Description
% CH_4 (Methane)	High CH_4 (≥ 98%) indicates (PD) Partial Discharge and low- energy insulation breakdown in transformer oil.
%C_2H_4(Ethylene)	Increase in C_2H_4 (<20% to ≥ 50%) indicates thermal faults, from low to high temperature overheating.
%C_2H_2(Acetylene)	Presence of C_2H_2 (≥ 4% to ≥ 29%) indicates electrical discharge/arcing faults such as D_1, D_2, and DT conditions.
Overall DGA Interpretation	Combinations of CH_4, C_2H_4, and C_2H_2 ratios is used to identify PD, Electrical energy discharge, and Thermal faults (T_1 - T_3).

Mathematical formulation

Duval Triangle Method (DTM)

The Duval triangle is a graphical and mathematical diagnostic technique developed for the interpretation of DGA results in oil-filled transformers. The DTM converts dissolved gas analysis data into normalized gas percentages values for precise fault identification. The method considers three key gases acetylene (C_2H_2), Ethylene (C_2H_4), Methane (CH_4), and normalizes their concentrations so that their total equal 100% and normalized values are then plotted on a triangular coordinate system, with each vertex representing the dominance of one gas. Unlike conventional ratio-based methods, the Duval triangle considers the simultaneous contribution of all three gases, thereby improving fault discrimination accuracy and reducing diagnostic uncertainty.

Initially, the concentration of C_2H_2, C_2H_4 , and CH_4 obtained from DGA are normalized into percentage values using the following equation.

$$\%CH_4 = \frac{k}{i+j+k} \times 100 \qquad \text{(i)}$$

$$\%C_2H_4 = \frac{j}{i+j+k} \times 100 \quad \text{(ii)}$$

$$\%C_2H_2 = \frac{i}{i+j+k} \times 100 \quad \text{(iii)}$$

Where i, j, and k are the concentrations of C_2H_2, C_2H_4, and CH_4, respectively, in ppm.

The normalized gas percentages satisfy the following condition

$$\%CH_4 + \%\ C_2H_4 + \%\ C_2H_2 = 100 \quad \text{(iv)}$$

The normalized gas percentage derived from equation (iv) sum to 100%, ensuring reliable fault classification within the Duval triangle. Following normalization through equations (i),(ii), and (iii), the relative concentrations of Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2) are mapped onto the Duval triangle, a ternary diagnostic framework based on barycentric coordinates and within this coordinate system, each vertex represents 100% concentration of a specific gas and 0% concentration of the remaining gases [17-20]. The plotted gas composition forms a unique coordinate point whose location within the designed fault regions enables precise diagnosis of the transformer fault condition. The resulting fault classification distinguishes PD, (D1, D2, DT) and (T1-T3). Consequently, the Duval triangle serves as a robust and widely accepted diagnostic tool for interpreting DGA data, facilitating accurate identification of incipient electrical and thermal faults in power transformer

Five-Gas Graphical (Duval Pentagon Method) Fault Diagnosis

Duval's Pentagon Method

The Duval Pentagon Method is an advanced extension of the Duval Triangle technique that improves fault diagnosis accuracy by incorporating hydrogen (H_2) and ethane (C_2H_6) as additional characteristic gases. The method determines the fault type by calculating the centroid of the geometric pattern formed by the concentrations of the characteristic gases. Using the pentagon method, we can detect five types of hydrocarbons gases. As the gas concentration increases, the fault condition becomes clear. The pentagon method is better than Duval triangle method [16].

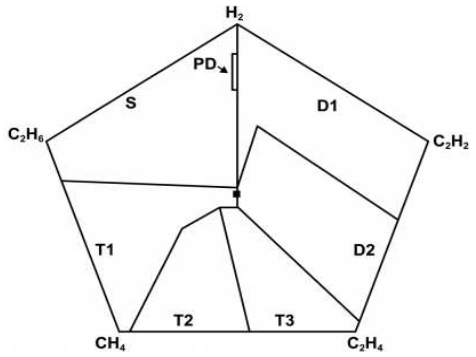


Fig. 4 Basic diagram of Duval Pentagon [2]

Result and Discussion

Doernenburg Ratio Method

DRM method is a four ratio and three fault classification and diagnosis. The obtained diagnosis indicates the presence of (PD, arcing, thermal decomposition) within the transformer insulation.

Table 7. DRM for fault classification

Data	R1	R2	R3	R4	Fault
1	0.0676	3.4067	17.0.33	0.0130	arcing
2	0.9667	1.3950	2.9344	0.0587	near arcing/undefined
3	0.3333	0.0454	0.0333	3	Indicative thermal decomposition

Roger's Ratio Method

This method does not provide accurate results. RRM is less effective in detecting incipient faults.

Table 8. Gas ratio interpretation by RRM

Data point	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	Fault
1	3.4067	0.0676	22.5	Electrical fault
2	1.395	0.967	7.33	T2-T2 fault
3	0.0454	0.333	7.3	T2

IEC Standard 60599

This method classified transformer faults into diagnosis six fault categories. Its similar ratio based on RRM but it is modified to improve thermal fault diagnosis. IEC Method may not provide exact fault severity, and location. Therefore, other diagnosis method to improving consistency.

Table 9. DGA-based as per IEC 60599

Data point	R1=CH_4/H_2	R2=C_2H_4/C_2H_6	R3=C_2H_2/C_2H_4
1	0.0676	22.5	3.4067
2	0.967	7.33	1.395
3	0.333	7.3	0.0454

Duval Triangle Method

This method is identified T3, D1, and D2 fault zones using the percentage of CH_4, C_2H_4, and C_2H_2 gases and details below table. The results indicate the insulation degradation, overheating, carbonization, and electrical discharge activity inside the transformer, providing more reliable fault interpretation than conventional gas ratio methods.

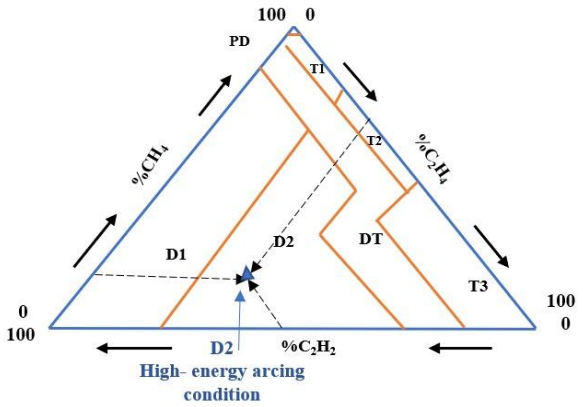


Fig. 5 High-energy discharged D2 fault located

As shown in fig. 4 D2 fault indicates high-energy electrical discharge or severe arcing inside the transformer. This fault causes extensive destruction of paper insulation. Where the cellulose insulation breaks into small fragments due to intense thermal stress and heat dissipation. A huge amount of carbon particles is generated and fragments in the transformer oil, indicating severe insulation deterioration and carbonization. Continuous D2 activity significantly weak dielectric strength of paper and oil insulation and may increase major internal transformer failure.

Table 10. Fault zone identification using DTM gas percentages

Data Point	%CH_4	%C_2H_4	%C_2H_2	Fault
1	5.19	88.45	6.34	D1
2	16.56	34.83	48.60	D2
3	3.19	95.74	1.06	T3

Duval Pentagon Method

Interpretation of the DGA Results

In the Duval Pentagon method, the percentage of hydrocarbon gases (%H_2,%CH_4, %C_2H_4, %C_2H_6, and %C_2H_2) is plotted to identify the fault zone [2]. For hydrocarbon gases analysis, the concentration of this hydrocarbon gases is expressed in terms of their percentage composition, as details below. where the measured concentrations of Hydrogen(H_2) below 5, Methane (CH_4) below 2, Ethane(C_2H_6) below 2, Ethylene(C_2H_4) at11, and Acetylene(C_2H_2) at 0.5, respectively, in ppm. When the mapping the five gas percentages value of a DGA sample over the pentagonal framework results in an irregular shaped polygon. The centroid of this irregular polygon associated the fault type [5-9].

Analysis of the percentage of gas according to fault types.

$$\% H_2 = \frac{H_2}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \times 100\%$$

$$\% C_2H_6 = \frac{C_2H_6}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \times 100\%$$

$$\% CH_4 = \frac{CH_4}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \times 100\%$$

$$\% C_2H_4 = \frac{C_2H_4}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \times 100\%$$

$$\% C_2H_2 = \frac{C_2H_2}{H_2+CH_4+C_2H_6+C_2H_4+C_2H_2} \times 100\%$$

S. No.	Gases	Percentages of gases
1	Hydrogen	24.3%
2	Ethane	9.7%
3	Methane	9.7%
4	Ethylene	53.6%
5	Acetylene	2.4%

Table11 Percentages of gases ration in Duval Pentagon Method

Centroid Coordinates calculation in fault zone

The horizontal x-axis and vertical y-axis are combined to determine the center of the pentagon. Subsequently, the centroid coordinates of the five red lines are computed, and the fault is plotted as shown in fig. 3. The blue points represent the fault points. The (x_k , y_k) coordinates of each of the five points are calculated [7]. For instance, for the point on the hydrogen H_2 axis, X1= (24.39%) cosα = 0, Y1 = (24.39%) sin α = 24.39. For the C_2H_6 axis, the angle α between the C_2H_6 axis and x-axis is 18 degrees left up. So, its coordinates are X2= (9.756%) cos α = -9.28and Y2= (9.756%) sin α =3.01. The same calculation is performed for other three points. In the example, the (x_k, y_k) coordinates for CH_4, C_2H_4, and C_2H_2, are (-5.74, -40.3), (31.55, -27.2), and (2.32,0.75), respectively [6-9].

$$C_Y = \frac{1}{6A}\left\{ \sum_{i=0}^{k-1}(y_k + y_{k+1})(x_{k,} y_{k+1} - x_{n+1,} y_k)\right\}$$

$$C_X = \frac{1}{6A} \sum_{i=0}^{k-1}(x_k + x_{k+1})(x_k, y_{k+1} - x_{k+1,} y_k)$$

$$A=\frac{1}{2}\sum_{i=0}^{k-1}(x_k, y_{k+1} - x_{k+1,} y_k)$$

Where:

Area (A) - Area of poly shape (surface of the polygon).

Centroid (C_X) - Centroid coordinates along Horizontal x-axis.

C_Y : Centroid coordinates along Vertical y-axis.

The area of the pentagon fault method is calculated using the relative concentrations of the five key gases as the vertices of the polygon [6]. Similarly, the centroid coordinates of the pentagon are determined by considering these gas concentrations as vertices. As shown by blue point figure 3 the calculated centroid coordinates are $C_x = 4.86$, C_y = -16.09. It is important to note that the center of an irregular polygon can also be determined mathematically by treating it as a center of mass by computing the average of its x_k and y_k coordinates [7-8]. However, in this paper it was preferred to calculate it using the centroid method for more precise representation. The arrangement of gases at the five vertices of the pentagon follows the increasing energy required to generate gas in transformers, from hydrogen to acetylene in a clockwise direction. This specific sequence was validated as providing the most accurate representation for fault identification in the pentagon diagram.

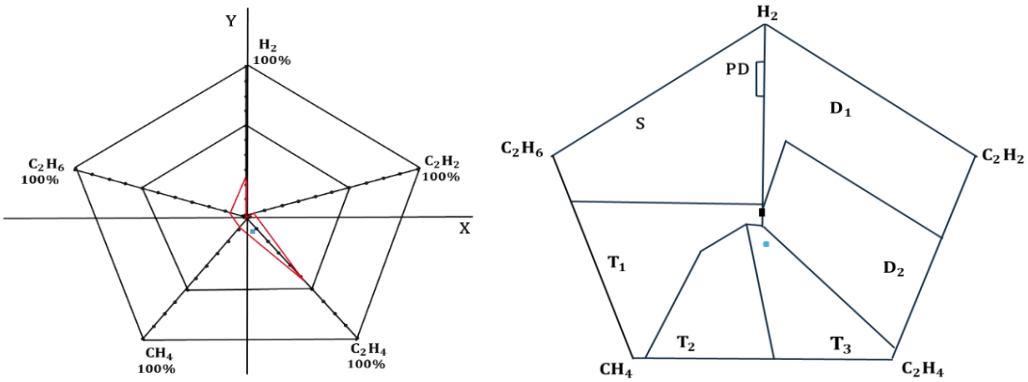


Fig. 6 Fault location in fault zone in pentagon using centroid method and Fault zones is indicated by blue point.

CONCLUSION

The investigation of failed power transformers presented in this paper indicates that the degradation of the oil–paper insulation system is one of the major contributing factors to transformer failure. The analysis of power transformer failure cases observed during the hot-climate period, particularly from April to June in the CSEB, shows that elevated ambient and operating temperature can accelerated the thermal aging of the insulation system. The increased temperature enhances insulation deterioration and can consequently lead to the generation and accumulation of dissolved gases in transformers oil. The post-failure dissolved gas analysis results indicate insulation degradation and faults. The Duval triangle method (DTM) effectively identifies the fault types and condition of the failed power transformers. Transformer failure are more frequent during hot climate conditions due to increased thermal stress. Therefore, after failure oil samples from a 132/33 kv power transformer were analyzed using DGA. Conventional dissolved gas analysis methods and the Duval triangle method was used to identify the fault zone and transformer condition, providing clear and accurate results, as show in Fig. 3 thermal faults (T3).

The finding of this study shows the importance of continuous monitoring of power transformer insulation condition, particular under high-temperature operating conditions, In future work, the proposed Dissolved gas analysis based diagnostic approach can be further extended by incorporating hot-climate operating conditions, seasonal temperature variations, and real-time monitoring parameters. The development of an integrated condition-monitoring system combining DGA, temperature, and other insulation- health indicators may provide an improved early-warning mechanism for detecting thermal aging and preventing unexpected transformer failures.

Acknowledgements

The author thanks the Chhattisgarh Electricity Board, Raipur, For sharing the data related to transformer failures and valuable support.

References

1. Rouse, T. O. (1998). Mineral insulating oil in transformers. *IEEE Electrical Insulation Magazine, 14*(3), 6-16. https://doi.org/10.1109/57.675572

2. Fernández, I., Ortiz, A., Delgado, F., Renedo, C., & Pérez, S. (2013). Comparative evaluation of alternative fluids for power transformers. *Electric Power Systems Research, 98*, 58-69.

3. Ranga, C., Kumar Chandel, A., & Chandel, R. (2017). Performance analysis of alternative solid dielectrics of power transformers with a blend of mineral and silicon oils. *IETE Technical Review, 35*(4), 331–341. https://doi.org/10.1080/02564602.2017.1299595

4. Ouyang, L., et al. (2023). High-performance medium- and long-chain diester electrical insulating oil biosynthesized via lipase catalyzation. *IEEE Transactions on Dielectrics and Electrical Insulation, 30*(6), 2819-2827. https://doi.org/10.1109/TDEI.2023.3294451

5. T. Manoj, C.Ranga, A Abu-Siada, and S.S.M. Ghoneim, "Analytic Hicrarchy Processed Grey Relational Fuzzy Approach for Health Assessment of Power Transformers," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 31, no. 3, pp. 1480-1489, Jun. 2024, doi:10.1109/iet.2024.3382076.

6. U. M. Rao, I. Fofana, A. Betie, M. L. Senoussaoui, M. Brahami and E. Briosso, "Condition monitoring of in-service oil-filled transformers: Case studies and experience," IEEE Electrical Insulation Magazine, vol. 35, no. 6, pp. 33-42, Nov.-Dec. 2019, doi: 10.1109/MEI.2019.8878258.

7. R. R. Rogers, "IEEE and IEC Codes to Interpret Incipient Faults in Transformers, Using Gas in Oil Analysis," IEEE Transactions on Electrical Insulation, vol. EI-13, no. 5, pp. 349-354, Oct. 1978, doi: 10.1109/TEI.1978.298141

8. M. Agouassi, U. M. Rao, Y. Hadjadj and I. Fofana, "On the Gassing Behaviour of Synthetic Ester Under Arcing Faults," 2023 IEEE Electrical Insulation Conference (EIC), Quebec City, QC, Canada, 2023, pp. 1-4, doi: 10.1109/EIC55835.2023.10177336.

9. T. Manoj, C. Ranga, S. S. M. Ghoneim, U. M. Rao and S. A. M. Abdelwahab, "Alternate and Effective Dissolved Gas Interpretation to Understand the Transformer Incipient Faults," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 30, no. 3, pp. 1231-1239, June 2023, doi: 10.1109/TDEI.2023.3237795.

10. K. N. V. P. S. Rajesh, U. M. Rao, I. Fofana, P. Rozga and A. Paramane, "Influence of Data Balancing on Transformer DGA Fault Classification With Machine Learning Algorithms," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 30, no. 1, pp. 385-392, Feb. 2023, doi: 10.1109/TDEI.2022.3230377.

11. S. Das, A. Paramane, S. Chatterjee and U. M. Rao, "Accurate Identification of Transformer Faults From Dissolved Gas Data Using Recursive Feature Elimination Method," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 30, no. 1, pp. 466-473, Feb. 2023, doi: 10.1109/TDEI.2022.3215936.

12. Teruvai Manoj, Chilaka Ranga, and U. M. Rao, "Multi-criterion fuzzy model for power transformer insulation monitoring," Electrical Engineering (2022) 104:3535–3546 https://doi.org/10.1007/s00202-022-01566-9

13. M. T. Agouassi, U. M. Rao, I. Fofana and Y. Hadjadj, "Understanding the Relationship Between Insulation Aging and Gassing Tendency of Some Biodegradable Dielectric Fluids," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 33, no. 1, pp. 302-309, Feb. 2026, doi: 10.1109/TDEI.2025.3596945.

14. M. Patil, A. Paramane, S. Das, U. M. Rao and P. Rozga, "Health Assessment of Solid Insulation of Mineral Oil-Filled Converter Transformer," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 31, no. 3, pp. 1557-1564, June 2024, doi: 10.1109/TDEI.2023.3347186.

15. F. F. Selim, M. A. Hassan, A. M. Azmy and E. G. Atiya, "Graphical Shape in Cartesian Plane Based on Dissolved Gas Analysis for Power Transformer Incipient Faults Discrimination," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 32, no. 1, pp. 589-597, Feb. 2025, doi: 10.1109/TDEI.2024.3404365.

16. IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers, IEEE Std C57.104-2019 (Revision of IEEE Std C57.104-2008) vol., no., pp.1-179, 1 Nov. 2019.

17. M. Duval, "Dissolved gas analysis: It can save your transformer," IEEE Electrical Insulation Magazine, vol. 5, no. 6, pp. 22-27, Nov.-Dec. 1989, doi: 10.1109/57.44605.

18. M. Duval and L. Lamarre, "The duval pentagon-a new complementary tool for the interpretation of dissolved gas analysis in transformers," IEEE Electrical Insulation Magazine, vol. 30, no. 6, pp. 9-12, November-December 2014, doi: 10.1109/MEI.2014.6943428.

19. M. Duval and L. Lamarre, “The new Duval Pentagons available for DGA diagnosis in transformers filled with mineral and ester oils,” IEEE Electrical Insulation Conference (EIC), Baltimore, MD, USA, 2017, pp. 279-281, doi: 10.1109/EIC.2017.8004683

20. P. Bourke, Calculating the Area and Centroïd of a Polygon. Available: http://paulbourke.net/geometry/polyarea.

21. C. Ranga and A. K. Chandel, “Multi-criterion approach for dissolved gas analysis of transformer oil,” IEEE UP Section Conference on Electrical Computer and Electronics (UPCON), Allahabad, India, 2015, pp. 1-6, doi: 10.1109/UPCON.2015.7456704.

22. A Abu-Siada and S. Islam, “A new approach to identify power transformer criticality and asset management decision based on dissolved gas-in-oil analysis,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 19, no. 3, pp. 1007-1012, June 2012, doi: 10.1109/TDEI.2012.6215106.

23. M. Duval and J. Buchacz, “Detection of Carbonization of Paper in Transformers Using Duval Pentagon 2 and Triangle 5,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 30, no. 4, pp. 1534-1539, Aug. 2023, doi: 10.1109/TDEI.2023.3278623.

24. M. Duval and J. Buchacz, “Identification of Arcing Faults in Paper and Oil in Transformers—Part I: Using the Duval Pentagons,” IEEE Electrical Insulation Magazine, vol. 38, no. 1, pp. 19-23, January/February 2022, doi: 10.1109/MEI.2022.9648268.