An Integrated, Multi-Method Software Platform for Advanced Dissolved Gas Analysis in Power Transformers

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Abstract- Dissolved Gas Analysis (DGA) is universally recognized as the most effective non-intrusive method for monitoring the condition of oil-immersed power transformers, providing critical insights into incipient thermal and electrical stresses. However, the diagnostic reliability of DGA is often challenged by the limitations of individual interpretation techniques, which can yield ambiguous or conflicting results for the same dataset. This article presents a comprehensive, client-side software analyzer designed to mitigate these uncertainties by integrating a suite of established and novel graphical DGA methods into a single, interactive platform. The tool automates the complex plotting and interpretation of the complete Duval Triangle suite (DT1, DT4, DT5), the advanced Duval Pentagons (DP1, DP2), and the prognostic Low Energy Degradation Triangle (LEDT). By synthesizing results from these complementary methodologies and incorporating advanced trend analysis, the platform enhances diagnostic accuracy and provides asset managers with a holistic, data-rich view of transformer health, facilitating more reliable and informed maintenance decisions.

I. INTRODUCTION

Power transformers are among the most critical and capital-intensive assets in electrical power systems, and their unexpected failure can lead to severe service interruptions and substantial economic losses. Consequently, condition monitoring is paramount for ensuring their operational reliability. Among the available diagnostic tools, Dissolved Gas Analysis (DGA) has emerged as the premier technique for the early detection of incipient faults in oil-immersed transformers. By analyzing the concentrations of various gases dissolved in the insulating oil—byproducts of the degradation of oil and solid insulation under electrical or thermal stress—DGA functions as a "blood test" for the transformer, revealing its internal health without the need for de-energization. Proactive maintenance strategies informed by DGA can prevent catastrophic failures, extend asset life, and optimize operational expenditures, underscoring its profound economic impact on asset management.

Evolution of Diagnostic Techniques

The interpretation of DGA data has evolved significantly over several decades. Early approaches relied on gas ratios to diagnose fault types, with pioneering work by Doernenburg and Rogers establishing foundational methods that are still referenced in industry standards like IEEE C57.104. These ratio-based techniques, however, are known to have limitations, such as producing "out-of-code" results when gas concentrations fall outside predefined ranges, leaving the fault unclassified. A major advancement came with the development of graphical methods, most notably the Duval Triangle, which visualizes the relative percentages of three key gases—methane (CH_4), ethylene (C_2H_4), and acetylene (C_2H_2)—to classify faults.

This shift towards graphical representation marked the beginning of a clear and persistent trend in DGA diagnostics: a move from simple, few-variable methods toward complex, multi-variable syntheses that provide increasingly granular diagnoses. The initial Duval Triangle (DT1) was later supplemented by specialized triangles (DT4, DT5) that use different gas combinations to refine specific fault types, such as stray gassing or paper carbonization. The next logical leap was the Duval Pentagon, which integrates five key gases into a single, more holistic graphic. The subsequent development of Pentagon 2, which uses the same five gases as Pentagon1 but with redefined zones to differentiate between faults in oil only (T3-H), faults involving paper (C), and low-level overheating (O), exemplifies the drive for ultimate diagnostic granularity. This progression demonstrates that achieving higher diagnostic certainty requires the synthesis of more comprehensive datasets.

The Challenge of Diagnostic Uncertainty

Despite these advancements, a fundamental challenge persists: different DGA interpretation methods can yield conflicting diagnoses for the same data. A ratio-based method might suggest a thermal fault, while a graphical method points to a low-energy discharge. This diagnostic ambiguity presents a significant problem for asset managers who must make critical decisions about maintenance, repair, or replacement. The path to higher diagnostic confidence, therefore, lies not in the pursuit of a single "perfect" method, but in the systematic and simultaneous application of multiple complementary techniques, where points of agreement reinforce a conclusion and points of disagreement trigger deeper investigation

Thesis Statement

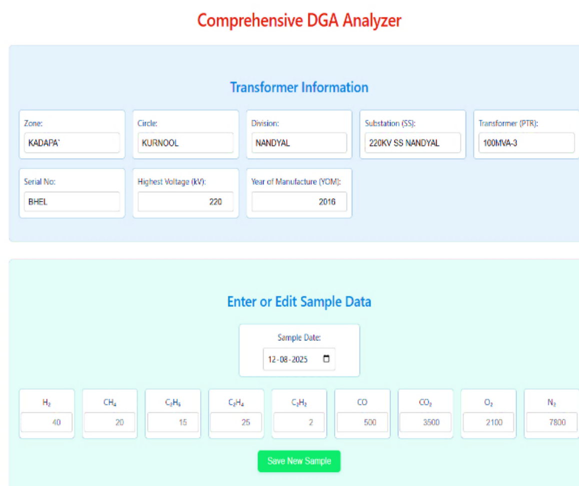
The integrated DGA analyzer detailed in this article is a software solution engineered to address this very challenge. By automating the complex plotting and interpretation of a wide array of methods—from the foundational Duval Triangle to the state-of-the-art Duval Pentagon 2 and the prognostic Low Energy Degradation Triangle (LEDT)—the tool provides engineers with a unified, data-rich dashboard. This integrated approach transforms DGA from a series of disjointed calculations into a cohesive analytical process, enabling more reliable and informed decision-making for transformer asset management.

II. SYSTEM ARCHITECTURE AND DIAGNOSTIC WORKFLOW

Client-Side Implementation

The analyzer is implemented as a standalone web application using standard HTML, CSS, and JavaScript, ensuring broad compatibility and ease of deployment. This client-side architecture offers several key advantages for use in the power industry.

- Portability and Accessibility: The tool requires no software installation and can be run in any modern web browser on any operating system. This allows engineers to perform analyses in the field on a laptop or tablet as easily as in the office.
- Data Security: All computations and data storage are handled exclusively on the user's local machine. Transformer data, which is often sensitive, is never transmitted to an external server. The application utilizes the browser's local Storage API to persist a history of samples, ensuring data privacy and aligning with the stringent security policies of utility companies.
- Performance and Responsiveness: The architecture is intentionally lightweight, avoiding heavy external frameworks and relying on the native HTML5 Canvas API for rendering all graphical diagrams. This direct approach ensures a fluid and responsive user experience, even when processing and displaying results from multiple complex diagnostic models simultaneously.



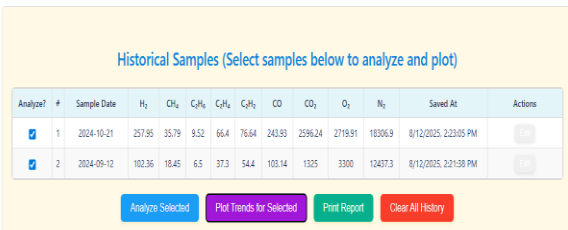
User-Centric Diagnostic Workflow

The user interface is structured to guide the engineer through a logical and efficient workflow, from data entry to final report generation.

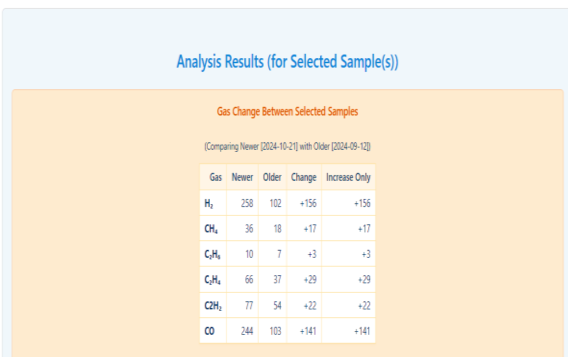
- Data Entry and Management: The primary input form accepts transformer metadata (e.g., location, ID) and the concentrations (in ppm) of nine key gases: hydrogen (H2), methane (CH4), ethane (C2H6), ethylene (C2H4), acetylene (C2H2), carbon monoxide (CO), carbon dioxide (CO2), oxygen (O2), and nitrogen (N2).
- Historical Data Table: Once entered, a sample can be saved to a persistent history table. This table

serves as the foundation for all time-based analysis, allowing users to store, retrieve, edit, or delete past samples. Engineers can select one or more samples from this table for analysis.

- Analysis Execution: Two primary actions drive the diagnostic process. Clicking "Analyze Selected" performs a comprehensive diagnosis on the chosen sample(s), populating the results panel with both textual interpretations and all graphical plots. Clicking "Plot Trends" generates a series of time-series charts for the selected historical data, enabling visualization of gas evolution over time.



Analyze?	#	Sample Date	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2	O_2	N_2	Saved At	Actions
☑	1	2024-10-21	257.95	35.79	9.52	66.4	76.64	243.93	2596.24	2719.91	18306.9	8/12/2025, 2:23:05 PM	Edit
☑	2	2024-09-12	102.36	18.45	6.5	37.3	54.4	103.14	1325	3300	12437.3	8/12/2025, 2:21:38 PM	Edit



Gas	Newer	Older	Change	Increase Only
H_2	258	102	+156	+156
CH_4	36	18	+17	+17
C_2H_6	10	7	+3	+3
C_2H_4	66	37	+29	+29
$C2H_2$	77	54	+22	+22
CO	244	103	+141	+141

III. CORE GRAPHICAL DIAGNOSTIC METHODOLOGIES

The true analytical power of the platform resides in its automated implementation and side-by-side presentation of multiple graphical DGA methods. This approach allows for immediate cross-validation of results, transforming the tool into an effective system for managing diagnostic uncertainty. For instance, a generic "T2" thermal fault indicated by one method can be instantly refined by another that specifies whether paper insulation is involved—a critical distinction for assessing fault severity. This system of checks and balances, where agreement builds confidence and disagreement prompts deeper investigation, is a core design principle.

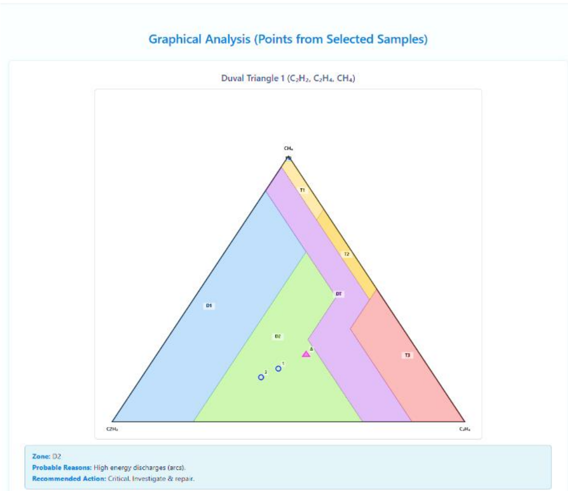
The Duval Triangle Suite: Foundational and Refined Fault Analysis

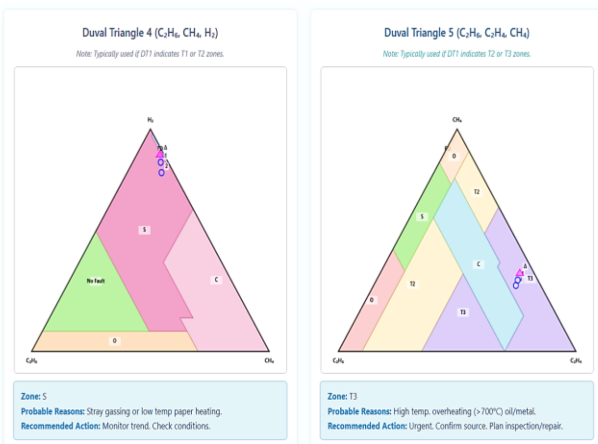
The Duval Triangle is the cornerstone of modern graphical DGA and serves as the tool's primary diagnostic starting point.

- Duval Triangle 1 (DT1): As the industry-standard first-line diagnostic, DT1 uses the relative percentages of three key combustible gases: methane (CH4), ethylene (C2H4), and acetylene (C2H2). The tool calculates the percentage of each gas relative to their sum and plots the resulting point within an equilateral triangle. The triangle is partitioned into seven internationally recognized fault zones: Partial Discharges (PD), Low-Energy Discharges (D1), High-Energy Discharges (D2), Thermal faults <300 deg C (T1), Thermal faults 300-700 deg C (T2), Thermal faults >700 deg C (T3), and a mixed thermal-electrical zone (DT). A key limitation of DT1, which the tool addresses through the inclusion of other methods, is its lack of a "normal" or "no-fault" zone; any significant gassing will be classified into a fault category.

- Duval Triangles 4 & 5 (DT4 & DT5): These are specialized, second-level diagnostic tools automatically employed by the analyzer to add critical nuance to specific findings from DT1.
  - DT4 is used to refine low-energy fault diagnoses (PD, T1, T2) from DT1. It utilizes a different gas set—hydrogen (H2), methane (CH4), and ethane (C2H6)—which are more indicative of low-energy processes. Its primary contribution is the ability to distinguish true low-energy faults from non-fault "Stray Gassing" (S) of oil, and to provide an indication of "Carbonization" (C) of paper at lower temperatures.
  - DT5 is applied when DT1 indicates a medium-to-high temperature thermal fault (T2, T3). It uses methane (CH4), ethylene (C2H4), and ethane (C2H6) to further characterize the fault. Its zones are designed to differentiate high-temperature faults occurring only in oil (T3) from those that involve the more serious

condition of paper insulation carbonization (C).

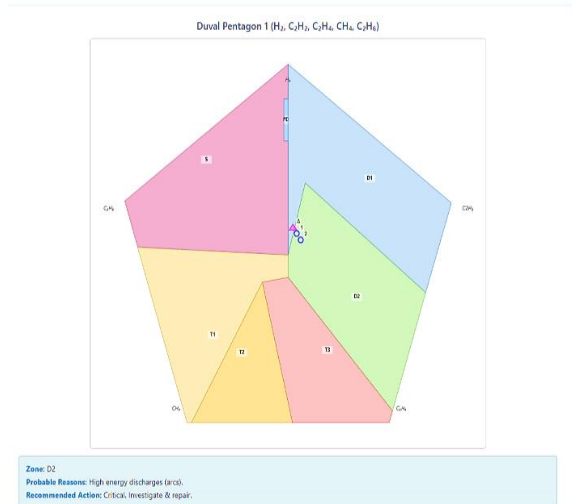




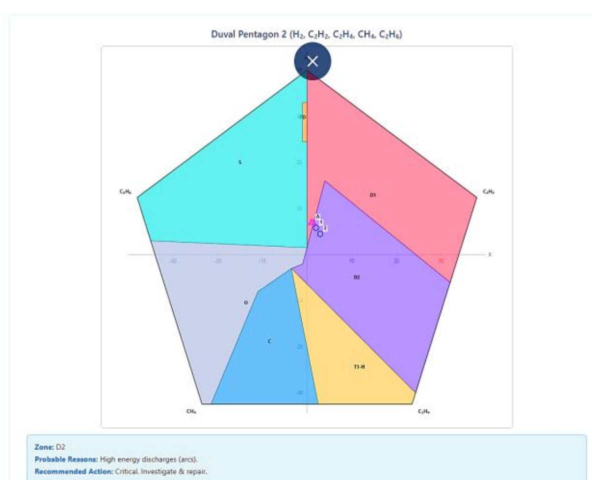
The Duval Pentagon Method: Comprehensive Five-Gas Diagnosis

The Duval Pentagon represents a significant evolution in DGA, incorporating five key combustible gases—H2, CH4, C2H6, C2H4, and C2H2—into a single, powerful graphical representation. The tool implements both generations of the Pentagon method. The diagnostic point is determined by first normalizing the five gas concentrations to percentages of their sum. These percentages are then used to define the vertices of an irregular polygon within the pentagon graphic, and the geometric centroid of this polygon is calculated to identify the fault zone.

Duval Pentagon 1 (DP1): This is the first-generation pentagon method. It provides a comprehensive diagnosis across seven zones analogous to DT1 (PD, D1, D2, T1, T2, T3), but with the important addition of an explicit zone for Stray Gassing (S), improving upon a known limitation of the basic triangle.



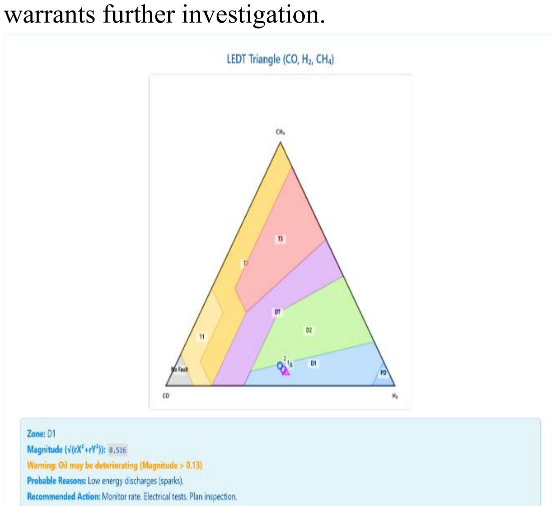
- Duval Pentagon 2 (DP2): Representing the current state-of-the-art, DP2 uses the same five gases and centroid calculation as DP1 but features redefined thermal fault zones that offer superior diagnostic granularity. The analyzer leverages DP2 to provide highly specific and actionable insights by distinguishing between three critical thermal conditions:
  - T3-H: A high-temperature thermal fault confined to the hydrocarbon oil only.
  - C: A thermal fault of any temperature range that involves the carbonization of paper insulation—a significantly more severe condition.
  - O: Low-temperature overheating (<250 deg C), often an incipient condition.



Low Energy Degradation Triangle (LEDT): Incipient Fault Detection

The analyzer also incorporates the Low Energy Degradation Triangle (LEDT), a distinct methodology focused on prognosis and early-stage fault detection. Its philosophy is to identify the subtle transition of a transformer from a healthy state to an incipient fault condition, often before significant levels of traditional fault gases like acetylene appear.

- Key Features: LEDT uses a unique set of low-energy gases: carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). The inclusion of CO makes it sensitive to the early stages of cellulose degradation. Its most significant advantage over DT1 is the inclusion of a defined "Normal" operating region, which occupies a corner of the triangle corresponding to high relative CO from slow, normal aging. As a fault develops, the plotted point migrates away from this "Normal" zone and toward regions corresponding to thermal faults (T1, T2, T3) or electrical discharges (PD, D1, D2).
- The R-Value Concept: To quantify this migration, LEDT employs the R-value, a metric representing the radial distance of the plotted point from the origin of the polar coordinate system. The analyzer calculates this value and flags when it crosses an empirically derived threshold (e.g., $R > 0.13$), providing a quantitative alert that abnormal insulation degradation is occurring and warrants further investigation.



IV. INTEGRATED CONVENTIONAL RATIO METHODS

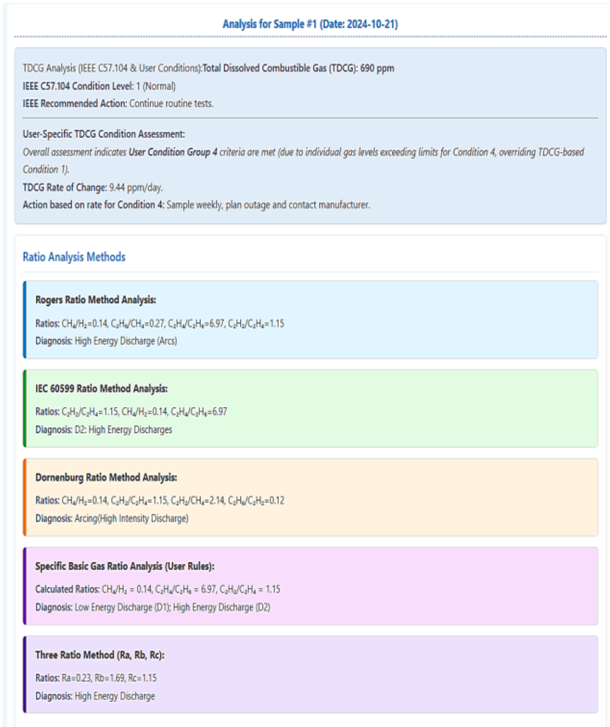
While graphical methods provide powerful visual diagnostics, the analyzer complements them by integrating a suite of conventional, ratio-based diagnostic techniques established in industry standards like IEEE C57.104 and IEC 60599. This parallel analysis provides an essential layer of cross-validation, where the concurrence between graphical and ratio-based results builds high diagnostic confidence. The tool automates the calculation and interpretation of several key ratio methods, presenting the findings as clear, textual diagnoses.

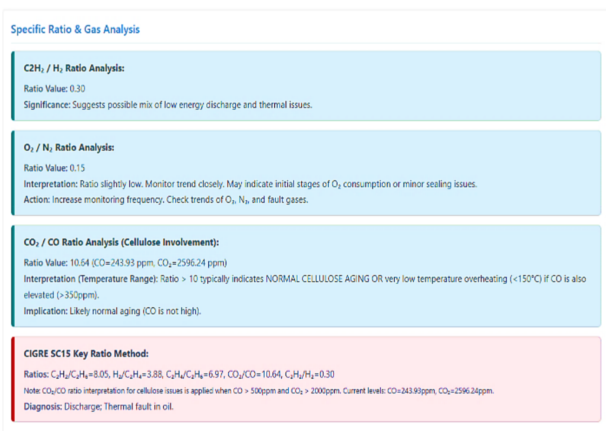
Rogers Ratio Method: A foundational technique that utilizes three key gas ratios (CH4/H2, C2H2/C2H4, and C2H4/C2H6) to classify faults. The software calculates these ratios and maps the results to the corresponding Rogers fault code, such as "High Energy Discharge (Arcs)". The implementation adheres to the classic tables where specific ratio ranges correspond to predefined fault cases.

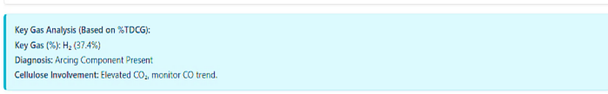
IEC 60599 Ratio Method: This method, widely used internationally, employs a similar set of ratios to Rogers but with a distinct interpretation scheme to yield codes such as PD, D1, D2, T1, T2, and T3. The tool checks that gas concentrations exceed the minimum levels required for the method to be valid, preventing misinterpretation from out-of-range data.

Dornenburg Ratio Method: An earlier but still referenced method that uses four different ratios (CH4/H2, C2H2/C2H4, C2H2/CH4, C2H6/C2H2). The analyzer computes these values and compares them against Dornenburg's criteria to identify faults like thermal decomposition or arcing.

Other Integrated Ratios: For comprehensive coverage, the tool also incorporates several other ratio-based diagnostics, including the IEEE "Basic Gas" Ratio Method, the Three-Ratio Method based on Japanese standards, and the CIGRE SC15 scheme. This multi-faceted approach ensures that if one method provides an ambiguous or "out-of-code" result, other methods are available to provide a clearer diagnosis, aligning with industry best practices for handling diagnostic uncertainty.







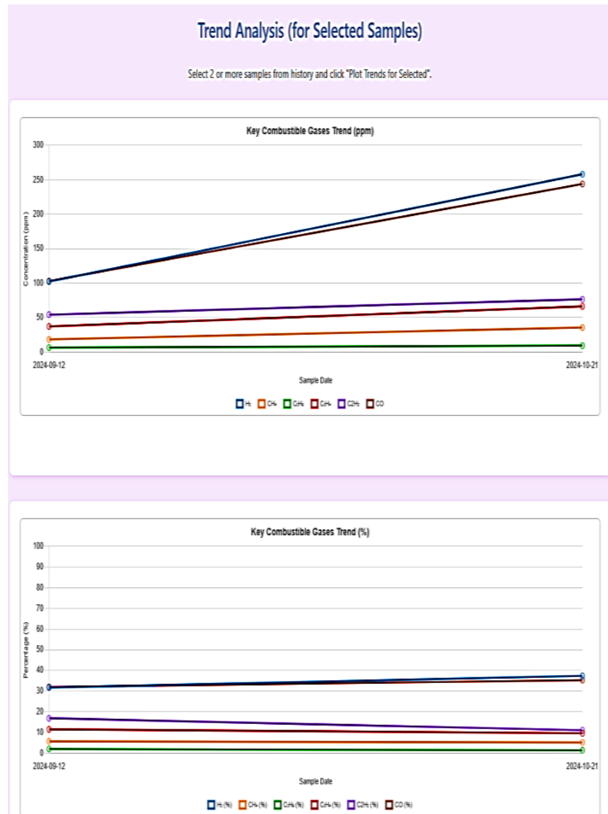
V. ADVANCED ANALYTICAL AND VISUALIZATION FEATURES

Beyond the core diagnostic plots, the analyzer provides supplementary features that deliver crucial context, enabling a deeper understanding of fault evolution and severity.

A. Historical Data Trending and Ratio Analysis

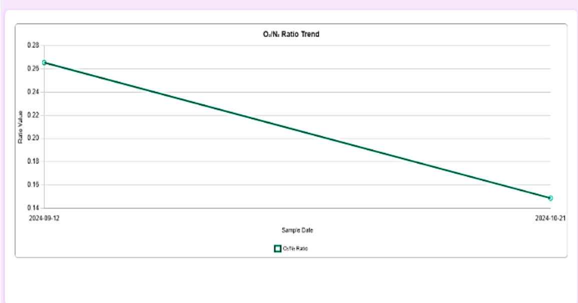
A single DGA sample provides a snapshot in time, but analyzing trends reveals the dynamics of a fault. The tool's "Plot Trends" function generates four essential time-series charts for any selected set of historical samples:

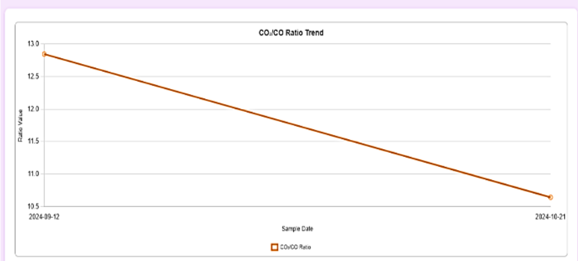
Key Gas PPM Trends: This chart plots the absolute concentration (ppm) of the key combustible gases over time. It provides a direct visualization of which gases are increasing and at what rate, offering a clear indication of a developing fault.



Gas Percentage Trends: This chart tracks the relative percentages of the combustible gases. It is a powerful complement to the Duval diagrams, as it explicitly shows the compositional shifts that cause a diagnostic point to move from one fault zone to another over time.

O2/N2 Ratio Trend: The ratio of dissolved oxygen to nitrogen is a valuable indicator of the transformer's sealing integrity. A stable, low ratio suggests a well-sealed unit, whereas a high or fluctuating ratio can indicate an air leak or that a fault is actively consuming oxygen. The tool plots this trend to provide context on the transformer's physical condition.

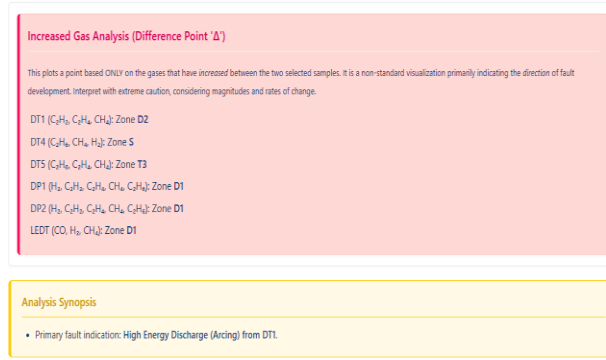




CO2/CO Ratio Trend: This ratio is a critical metric for assessing the nature of cellulose insulation degradation. A low ratio (<3) often points to severe, high-temperature degradation or arcing involving paper, while a high ratio (>7) typically indicates lower-temperature thermal degradation or normal aging. Tracking this ratio over time can signal an escalating thermal fault involving solid insulation.

B. Increased Gas Analysis for Fault Evolution Tracking

To quantify the change between two specific points in time, the tool offers an "Increased Gas Analysis" feature. When an engineer selects exactly two samples, the software calculates the difference (\Delta) in concentration for each gas. This set of delta values is then treated as a new, virtual sample and is plotted on all the diagnostic diagrams. This "\Delta point" visualizes the *character* of the fault's evolution. For example, if the absolute DGA values for a transformer are in a T2 (thermal) zone, but the \Delta point between the last two samples falls in the D1 (discharge) zone, it provides strong evidence that a new electrical fault is developing on top of a pre-existing thermal condition.



VI. CONCLUSION

This article has detailed an integrated, multi-method software platform for the advanced analysis of dissolved gas data from power transformers. The tool's core strength lies in its synthesis of a comprehensive suite of diagnostic methodologies within a secure, accessible, and user-centric architecture. By automating the application of the Duval Triangle suite, the advanced Duval Pentagons, and the prognostic LEDT, and supplementing these with powerful features for trend and evolutionary analysis, the platform provides an unparalleled depth of insight into transformer condition.

The central argument of this work is that a multi-method approach, as facilitated by this tool, is superior for managing the inherent uncertainties of DGA and achieving high-confidence fault identification. A practical case study demonstrates this principle effectively: for a transformer exhibiting a developing fault, the tool's analysis showed that Duval Triangle 1, Duval Pentagon 1, and Duval Pentagon 2 all converged on a "D2" (High-Energy Discharge) diagnosis. This unambiguous result, further corroborated by multiple conventional ratio methods, provided a clear and immediately actionable conclusion that an arcing fault was present and escalating. This level of diagnostic certainty is difficult to achieve when relying on a single, isolated technique.

In the broader context of digital transformation in the power industry, tools like this DGA analyzer are pivotal. By making sophisticated diagnostics accessible, repeatable, and easy to document, such software empowers utilities to transition from inefficient time-based or reactive maintenance paradigms to more cost-effective and reliable condition-based asset management strategies. This shift not only enhances the reliability and extends the operational life of critical transformer assets but also contributes significantly to the stability and resilience of the entire electrical grid.

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