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RESEARCH ARTICLE

Optimizing Power Transformer Failure Identification: A Multi-Method Framework Based on Normalized Energy Intensity According to IEEE C57.104-2019 Standards Adapted to Indonesian Power Transformer Characteristics

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Abstract

This research develops and validates a multi-method diagnostic framework by integrating Normalized Energy Intensity (NEI) parameters in accordance with IEEE C57.104-2019 standards adapted to the characteristics of the Indonesian power transformer population. The proposed framework offers failure severity validation previously unavailable in conventional Dissolved Gas Analysis (DGA) methods, resulting in consistent fault type patterns across severity levels. Analysis of 1525 DGA samples from PLN Indonesia transformers reveals significant differences in percentile thresholds compared to North American references. Applying unadapted North American thresholds classifies 68.4% of transformers as critical (DGA Status 3), while locally adjusted thresholds reduce this figure to 25.1%. Duval Triangle 1 identifies Discharge of Low Energy (D1) as the dominant failure type (35.4%), while Duval Pentagon 1 highlights Discharge of High Energy (D2) (39.4%), and Duval Pentagon 2 indicates Stray gassing (S) (27.6%) and Overheating without paper carbonization (O) (22.3%). Pearson correlation analysis on transformers with O_2/N_2 ratio ≤ 0.2 shows strong correlations between NEI Oil and ethylene (R=0.877) as well as methane (R=0.845), while NEI Paper correlates strongly with carbon monoxide (R=0.934). NEI Oil, when combined with hydrocarbon gas concentrations, provides more consistent pattern alignment in multi-method failure identification compared to NEI Paper. Multi-method validation proved absolute gas concentration methods more reliable than gas ratio methods. This framework improves maintenance efficiency by reducing false alarms and optimizing preventive strategies.

Keywords: Power Transformer, Dissolved Gas Analysis, Normalized Energy Intensity, IEEE C57.104-2019, Duval Triangle, Duval Pentagon, Percentile Threshold, Fault Identification, Multi-Method

1. Introduction

This research aims to develop and validate a multi-method DGA diagnostic framework that integrates NEI parameters and is adapted to the characteristics of power transformer populations in Indonesia based on the IEEE C57.104-2019 standard [1, 2, 3, 4]. Specifically, this research aims to: (1) evaluate the correlation between dissolved gas concentrations and NEI values in transformer oil and paper insulation [1, 5, 6, 7] ; (2) identify the best DGA interpretation method through a multi-method approach, focusing on Duval Triangle and Duval Pentagon [8, 2, 9, 10] ; (3) establish percentile-based gas concentration threshold values for the Indonesian transformer population [2, 11, 4, 12] ; and (4) develop an adaptive and valid diagnostic framework to detect the type and severity of transformer failures in the context of the Indonesian electricity system [13, 14, 15, 16]. By achieving these objectives, the research is expected to make a significant contribution to improving the reliability and efficiency of power transformer condition monitoring, which in turn will strengthen the resilience of the national electricity system [3, 17, 18, 19].

Recent literature reviews indicate significant evolution in Dissolved Gas Analysis (DGA) interpretation methods, from conventional approaches such as Rogers Ratio and Key Gas Method to more sophisticated techniques such as Duval Triangle and Duval Pentagon [20, 21, 22, 23]. Duval (2014) introduced the Duval Pentagon as a complementary tool for DGA interpretation, offering improved diagnostic capabilities for mixed failures [8, 24, 9, 10] . Meanwhile, Paul and Goswami (2022,2024) developed a bivariate Normalized Energy Intensity (NEI) model for oil and insulation paper, providing a quantitative framework for failure severity evaluation [1, 5, 25, 7]. In Indonesia, several case studies have been conducted by Prasojo et al. (2022) and Surawijaya et al. (2019) on mixed failure identification and diagnosis of geothermal power transformers, but there has not been a comprehensive approach that integrates multi-methods with NEI parameters and is adapted to the characteristics of the local transformer population [14, 3, 26, 17]. The updated IEEE C57.104-2019 standard offers a more comprehensive framework by introducing the concept of NEI, however Draper et al. (2022) identified the need for improvements in interpreting failure severity levels based on this standard [2, 11, 4, 12]. Identified research gaps include: (1) lack of validation of multi-method DGA interpretation methods for the Indonesian transformer population [27, 14, 3, 28] ; (2) absence of established percentile-based threshold values specific to transformers in Indonesia [2, 11, 4, 29]; (3) limited understanding of the correlation between dissolved gases and NEI parameters in the local context [1, 6, 25, 30]; and (4) lack of an integrated diagnostic framework that is adaptive to the characteristics of Indonesian transformers [13, 14, 25, 31].

Adaptation of NEI threshold values for the Indonesian context represents a significant methodological contribution as it provides failure severity validation previously unavailable in conventional DGA methods [13, 14, 32]. This research is the first study to comprehensively analyze the correlation between dissolved gas concentrations and NEI values in an Indonesian transformer population with 1525 samples, resulting in consistent fault type patterns from low to high severity levels [1, 32, 15]. As shown in Fig. 5, using North American threshold values without adaptation resulted in 68.4% of transformers being categorized as DGA Status 3 (critical), while with adjusted threshold values, only 25.1% of transformers fell into this category [33, 2, 34]. This dramatic difference not only reduces false alarms and unnecessary maintenance actions but also enables more accurate identification of failure patterns based on specific key gas combinations with optimal interpretation methods for each type of failure [35, 36, 37]. Research results show that ethylene becomes the main indicator of high-temperature thermal failures (T3) with the highest correlation (R=0.877) and methane (R=0.845) becomes the most consistent indicator across all interpretation methods, providing a more comprehensive and adaptive diagnostic framework compared to conventional TDCG-based or gas ratio approaches [8, 38, 39].

2. IEEE C57.104-2019 Standards: Evolution and Implementation Framework

The IEEE C57.104-2019 standard represents a significant evolution in the interpretation of Dissolved Gas Analysis (DGA) for oil-immersed power transformers [2, 4, 12]. This standard, which is a revision of IEEE C57.104-2008, has undergone substantial changes in the approach to transformer failure diagnosis [21, 11, 4, 29]. One fundamental change is the introduction of the Normalized Energy Intensity (NEI) concept as a new parameter for failure severity evaluation [1, 5, 25, 30]. This standard also adopts a more comprehensive approach in classifying transformer conditions based on dissolved gas concentrations, taking into account additional factors such as certain gas ratios and transformer age [20, 40, 41, 42].

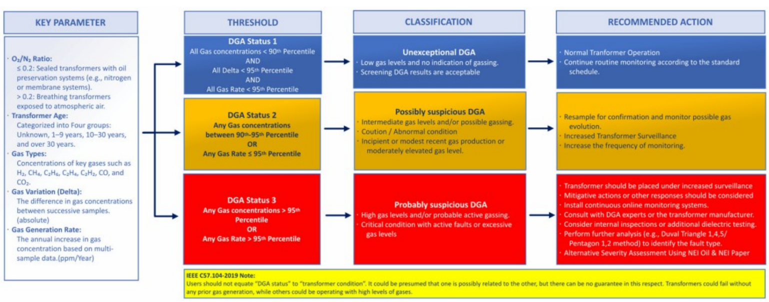

Figure 1. General guide for classification and recommended actions based on DGA status according to IEEE C57.104-2019 standard [43]

Figure 1 illustrates the general approach of IEEE C57.104-2019 in classifying transformer conditions based on key parameters such as O_2/N_2 ratio, transformer age, gas type, gas variation (Delta), and gas formation rate [2, 4, 44, 12]. This standard classifies transformers into three DGA statuses: Status 1 (Unexceptional DGA) for transformers with gas concentrations below the 90th percentile, Status 2 (Possibly suspicious DGA) for transformers with gas concentrations between the

90th and 95th percentiles, and Status 3 (Probably suspicious DGA) for transformers with gas concentrations above the 95th percentile [45, 46, 4, 47]. This classification is then correlated with appropriate action recommendations, ranging from routine monitoring to indepth inspection and advanced analysis using methods such as Duval Triangle and Duval Pentagon [8, 24, 48, 9].

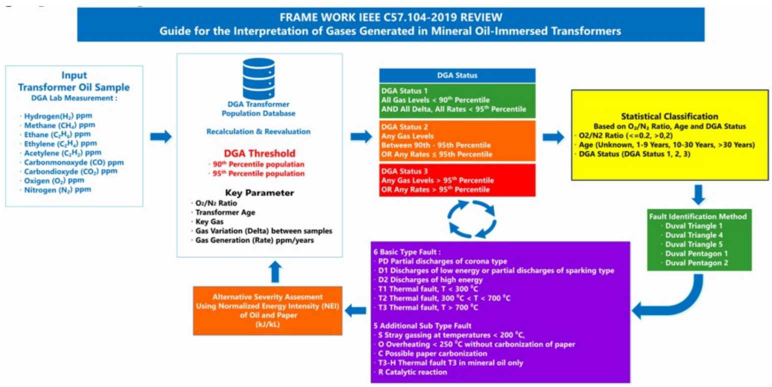

Figure 2. Framework implementation of IEEE C57.104-2019 standard for transformer condition assessment and fault identification

Figure 2 presents a more detailed implementation framework of IEEE C57.104-2019, showing the process flow from transformer oil sampling to failure diagnosis [49, 34, 4, 50]. This framework includes several key components: a transformer population database for evaluation and recalculation of DGA thresholds, statistical classification based on O_2/N_2 ratio and transformer age, and failure identification methods using Duval Triangle (1,4,5) and Duval Pentagon (1,2) [51, 24, 52, 10]. This standard identifies six basic types of failures (PD, D1, D2, T1, T2, T3) and five additional failure subtypes (S, O, C, T3-H, R), providing a comprehensive picture of transformer conditions [35, 53, 54, 55]. The implementation of this framework in Indonesia requires adaptation to the characteristics of local transformer populations, with determination of percentile threshold values based on historical data collected from PLN power transformers throughout Indonesia [13, 14, 3, 17].

The IEEE C57.104-2019 standard introduces the concept of Normalized Energy Intensity (NEI) as a quantitative parameter for evaluating the severity of transformer failures [1, 14, 56]. NEI is a metric that measures the energy intensity required to produce certain dissolved gases, providing a quantitative indication about the severity level of failures [15, 57]. There are two types of NEI used in transformer diagnostics: NEI Oil and NEI Paper [1, 14, 32]. NEI Oil measures fault energy that damages the liquid insulation (oil) of transformers, calculated based on the concentration of dissolved hydrocarbon gases (methane, ethane, ethylene, and acetylene) [32, 15, 56]. This value provides an indication about the energy released during failure processes affecting the insulation oil [14, 32, 58]. Meanwhile, NEI Paper measures fault energy affecting the solid insulation (paper) of transformers, calculated based on the concentration of carbon monoxide and carbon dioxide [1, 14, 59]. This value provides information about the degradation of paper insulation which is a critical component in transformer insulation systems [13, 40, 59]. The separation of these two NEI parameters enables a more comprehensive evaluation of transformer conditions, where NEI Oil and NEI Paper can show different patterns depending on the type of failure occurring [1, 14, 32].

3. Methods

This research develops a comprehensive methodological framework for power transformer condition evaluation based on IEEE C57.104-2019 standards that have been adapted to the characteristics of the transformer population in Indonesia [60, 13, 43] . Fig. 3 illustrates the systematic approach used, representing the entire optimization process for transformer failure identification based on Dissolved Gas Analysis (DGA) and Normalized Energy Intensity (NEI) parameters [1, 14, 32]. The framework begins with collection of transformer oil samples that are analyzed to determine dissolved gas concentrations (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, O_2, N_2) and calculation of normalized energy intensity (NEI) values for oil and paper insulation [35, 40, 57]. The developed methodology integrates analysis of the PLN Indonesia transformer population database with DGA threshold values based on 90th and 95th percentiles [33, 61, 12] . Key parameters such as O_2/N_2 ratio, transformer age, and gas variations (Delta and Rate) are used for transformer condition classification [45, 62, 11].

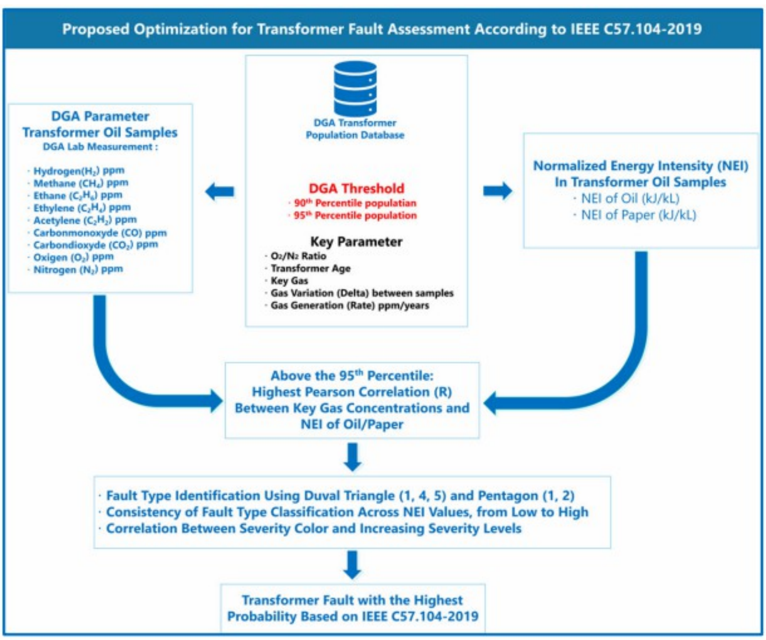

Figure 3. Proposed Optimization Framework for Transformer Fault Identification According to IEEE C57.104-2019

This methodological approach uniquely optimizes the failure identification process through Pearson correlation (R) evaluation between key gas concentrations and NEI values for oil and paper insulation, enabling more accurate failure identification using Duval Triangle and Pentagon methods [8, 63, 64]. This correlation analysis provides deep insights into the relationship between dissolved gas parameters and failure severity levels, resulting in a more adaptive diagnostic framework suitable for the characteristics of transformers in Indonesia [38, 48, 39].

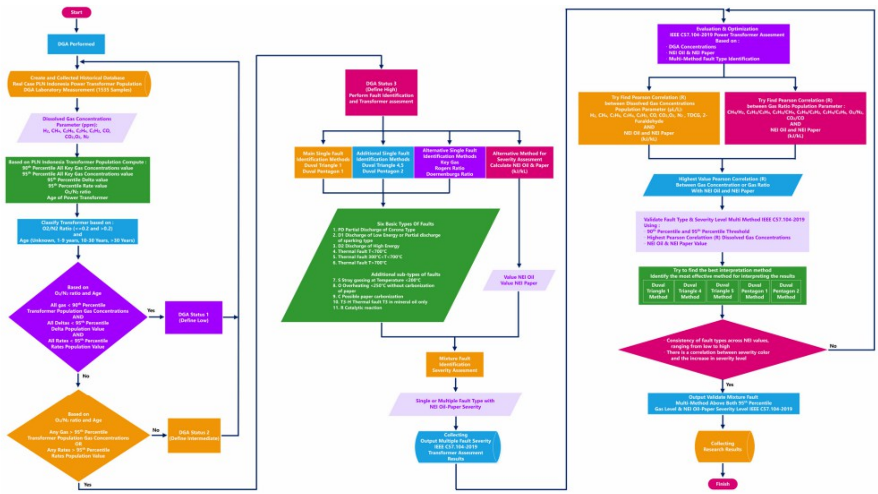

Figure 4. Research Flow Chart for Multi-Method Fault Identification Using Normalized Energy Intensity Based on IEEE C57.104-2019

Figure 4 shows the research process flow in more detail, covering the stage of historical data collection through DGA laboratory testing with 1525 samples[35, 20, 65, 66], establishment of threshold percentile values based on the PLN Indonesia transformer population[13, 67, 34, 68], transformer classification based on O_2/N_2 ratio and age[4, 29, 69, 70], failure identification using various methods (Duval Triangle, Duval Pentagon, Rogers Ratio, Key Gas, and Doernenburg Ratio)[45, 27, 53, 48, 71, 72], as well as optimization and validation of research results[49, 37, 55, 73]. This methodological framework allows evaluation of the consistency of failure type identification at various NEI value levels and correlation between severity indicators with energy intensity levels, resulting in a more adaptive and accurate approach for power transformer condition assessment in Indonesia[60, 33, 74, 75, 6, 76, 77].

3.1 Percentile-Based Threshold Determination

Based on the statistical distribution of 1525 data samples, threshold values for each gas were established using a percentile-based approach, specific to the Indonesian transformer population[78, 79, 34, 43]. The 90th, 95th, and 99th percentile values were selected as thresholds for each gas, in accordance with IEEE C57.104-2019 recommendations[33, 5, 61, 80]. This approach allows classification of transformer conditions into three DGA statuses: Status 1 (gas concentration below the 90th percentile), Status 2 (gas concentration between the 90th and 95th percentiles), and Status 3 (gas concentration above the 95th percentile)[51, 81, 82, 10]. The 99th percentile-based threshold is used to identify extreme cases requiring immediate attention[36, 83, 72, 84]. These threshold values were further divided based on O_2/N_2 ratio (≤ 0.2 and > 0.2) and transformer age groups, resulting in a more specific threshold matrix that corresponds to the characteristics of the transformer population in Indonesia[38, 71, 85, 86]. The calculation of the Pp-th percentile for a series of values sorted from smallest to largest can be done using the formula:

$$x_{\lfloor n.p/100 \rfloor} + \left(n.\frac{p}{100} - \left\lfloor n.\frac{p}{100} \right\rfloor \right) . \left(x_{\lceil n.p/100 \rceil} - x_{\lfloor n.p/100 \rfloor} \right) \tag{1}$$

for each percentile:

90th Percentile: $P_{90} = x_{\lfloor n.0.9 \rfloor} + (n.0.9 - \lfloor n.0.9 \rfloor) . \left(x_{\lceil n.0.9 \rceil} - x_{\lfloor n.0.9 \rfloor} \right)$

95th Percentile: $P_{95} = x_{\lfloor n.0.95 \rfloor} + (n.0.95 - \lfloor n.0.95 \rfloor) . \left(x_{\lceil n.0.95 \rceil} - x_{\lfloor n.0.95 \rfloor} \right)$

99th Percentile: $P_{99} = x_{\lfloor n.0.99 \rfloor} + (n.0.99 - \lfloor n.0.99 \rfloor) . \left(x_{\lceil n.0.99 \rceil} - x_{\lfloor n.0.99 \rfloor} \right)$

where n is the number of samples, P_p is the desired percentile, and x_i is the value at the i-th order that has been sorted from small to large, $\lfloor . \rfloor$ indicates rounding down (*floor*) and $\lceil . \rceil$ indicates rounding up (*ceiling*) [46, 76, 87, 38, 86].

3.2 Normalized Energy Intensity (NEI) Calculation and Implementation

This research implements the Normalized Energy Intensity (NEI) concept in accordance with IEEE C57.104-2019 standard to evaluate the severity of transformer failures [1, 63, 46, 56]. NEI is a metric that measures the energy intensity required to produce certain dissolved gases, providing a quantitative indication of failure severity [14, 15, 57]. Two NEI parameters are calculated: NEI Oil for evaluating failure severity in insulating oil (based on dissolved hydrocarbon gas concentrations) and NEI Paper for evaluating failures affecting paper insulation (based on carbon monoxide and carbon dioxide concentrations) [32, 41, 55]. The calculated NEI values are then evaluated against the statistical distribution of the Indonesian transformer population to determine failure severity levels, with the 90th, 95th, and 99th percentile values used as thresholds for severity classification [40, 88, 31]. NEI Oil is calculated based on the concentration of dissolved hydrocarbon gases (methane, ethane, ethylene, and acetylene) using the formula[1, 14, 40]:

$$NEI_{oil} = \frac{77.7 \times [CH_4] + 93.5 \times [C_2H_6] + 104.1 \times [C_2H_4] + 278.3 \times [C_2H_2]}{22400} \tag{2}$$

Meanwhile, *NEI Paper* is calculated based on the concentrations of carbon monoxide and carbon dioxide with the formula[1, 40, 41]:

$$NEI_{paper} = \frac{101.4 \times [CO] + 30.2 \times [CO_2]}{22400} \tag{3}$$

In both formulas, gas concentrations are expressed in μL/L (ppm), corrected at standard temperature and pressure (273.15 K and 101.325 kPa)[79, 43, 57]. The numerical coefficients for each gas represent the standard heat of formation of that gas from typical mineral oil (for NEI Oil) or typical cellulose monomer (for NEI Paper)[1, 14, 56].

3.3 Pearson Correlation Analysis for Gas-NEI Relationship

This research uses Pearson correlation analysis (R) to evaluate the relationship between dissolved gas concentrations, gas ratios, and NEI values [38, 52, 89, 30]. The Pearson correlation coefficient measures the strength and direction of the linear relationship between two variables, with values ranging from –1 to +1 [74, 61, 86, 90]. This correlation analysis aims to identify gases or gas ratios that have the most significant relationship with NEI values, which can be used as better indicators for failure severity [91, 32, 25, 73]. The analysis is conducted in several stages: evaluation of correlations between individual gas concentrations and NEI Oil and NEI Paper values; evaluation of correlations between gas ratios and NEI values; and evaluation of correlations between gas concentrations and gas ratios with transformer operational parameters [33, 66, 92, 93]. The results of this analysis are used to identify the best indicators for failure severity [36, 37, 94, 16]. The Pearson correlation coefficient is calculated using the formula:

$$R = \frac{\sum_{i=1}^{n} (X_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (X_1 - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} \tag{4}$$

where x_i and y_i are the values of the two correlated variables, $\bar{x}$ and $\bar{y}$ are the mean values, and n is the number of samples [8, 38, 77, 39, 87].

4. Result and Discussion

4.1 Classification Results of Transformer in the Indonesian Population Based on Adopted C57.104-2019 Standard

Classification of transformer conditions in the Indonesian population based on the adapted IEEE C57.104–2019 standard reveals a unique and specific dissolved gas distribution for local transformer characteristics [79, 43, 16, 80]. Analysis of 1525 DGA data samples from PLN Indonesia transformers shows significant differences in threshold values based on O_2/N_2 ratio [1, 60, 2, 61, 76] . As shown in Table 1, transformers with O_2/N_2 ratio ≤ 0.2 exhibit hydrogen gas (H_2) concentrations at the 90th, 95th, and 99th percentiles of 243 ppm, 279 ppm, and 372 ppm respectively, while transformers with O_2/N_2 ratio >0.2 have different values of 256 ppm, 379 ppm, and 1162 ppm [35, 36, 91, 52, 62]. Similar patterns are also observed in other gases such as methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2) [95, 8, 24, 63, 17, 22] .

The results of Delta gas analysis in Table 2 show that the change in hydrogen gas (H_2) concentration at the 95th percentile reaches 93 ppm for transformers with O_2/N_2 ratio ≤ 0.2 and 96 ppm for transformers with O_2/N_2 ratio >0.2 [20, 53, 48, 21, 68, 92]. Meanwhile, Table 3 displays the gas change rate (Rate) at the 95th percentile with varying patterns based on measurement period and O_2/N_2 ratio [32, 40, 34, 15, 77, 39] . These values form the basis for classifying transformer conditions into

Table 1. 90th, 95th and 99th Percentile Gas Level (ppm) Based on IEEE C57.104-2019 Indonesian Transformer Population Result[43].

Parameter	O_2/N_2 Ratio ≤ 0.2 (n=1423)			O_2/N_2 Ratio > 0.2 (n=112)		
	90th Percentile	95th Percentile	99th Percentile	90th Percentile	95th Percentile	99th Percentile
Hydrogen (ppm)	243	279	372	256	379	5162
Methane (ppm)	354	837	2882	72	172	2645
Ethane (ppm)	146	246	775	16	154	941
Ethylene (ppm)	86	154	2192	54	2129	16240
Acetylene (ppm)	176	278	580	8	92	1167
Carbonmonoxyde (ppm)	929	1134	1926	1590	2532	5477
Carbondioxyde (ppm)	6112	7688	11848	6673	10288	23527
Oxygen (ppm)	6782	8843	12126	102117	142621	359029
Nytrogen (ppm)	85300	94128	118613	38022	64502	72993
TDCG (ppm)	1535	1999	8275	2708	6359	27066
2FAL (ppb)	600	2221	4522	993	2298	4476
NEI Paper (kJ/kL)	12	14	22	15	29	49
NEI Oil (kJ/kL)	4	7	25	1	19	106

three DGA statuses (Status 1, 2, and 3) that correspond to the characteristics of the transformer population in Indonesia [33, 13, 67, 6, 94, 86] .

Table 2. 95th Percentile Delta Gas Concentration (ppm) Based on IEEE C57.104-2019 Indonesian Transformer Population Result[43].

Parameter (Delta)	O_2/N_2 Ratio ≤ 0.2 (n=1423)			O_2/N_2 Ratio > 0.2 (n=112)		
	90th Percentile	95th Percentile	99th Percentile	90th Percentile	95th Percentile	99th Percentile
Hydrogen Delta	7	93	260	63	96	250
Methane Delta	24	80	617	0	10	82
Ethane Delta	0	2	43	0	0	1
Ethylene Delta	3	17	124	0	4	11
Acetylene Delta	8	63	253	0	0	18
Carbonmonoxyde Delta	114	255	705	42	734	2246
Carbondioxyde Delta	862	2384	5245	289	1278	5454

Table 3. 95th Percentile Rate of Gas Generation (ppm/year) Based on IEEE C57.104-2019 Indonesian Transformer Population Result [43].

Parameter (Rate)	O_2/N_2 Ratio ≤ 0.2 (n=1423)						O_2/N_2 Ratio > 0.2 (n=112)					
	90th Percentile		95th Percentile		99th Percentile		90th Percentile		95th Percentile		99th Percentile	
	4-9 Month	10-24 Month	4-9 Month	10-24 Month	4-9 Month	10-24 Month	4-9 Month	10-24 Month	4-9 Month	10-24 Month	4-9 Month	10-24 Month
Hydrogen Rate	0	0	0	0	325	17	4	0	109	0	285	0
Methane Rate	0	0	48	0	455	66	0	0	0	0	25	0
Ethane Rate	0	0	0	0	12	1	0	0	0	0	2	0
Ethylene Rate	0	0	0	0	67	2	0	0	0	0	22	0
Acetylene Rate	0	0	5	0	289	94	0	0	0	0	3	0
Carbonmonoxyde Rate	0	0	171	0	961	305	15	0	703	0	2804	0
Carbondioxyde Rate	0	0	235	0	7567	3164	0	0	1080	0	13959	0

4.2 Comparison of Percentile Threshold Values with IEEE C57.104-2019 Standard

Figure 5 illustrates the dramatic differences in the distribution of DGA status generated when applying the threshold values of the North American standard IEEE C57.104-2019 compared to threshold values adapted for the Indonesian transformer population [79, 68, 43, 80]. For transformers with an O_2/N_2 ratio ≤ 0.2, using the North American standard threshold values results in 974 transformers (68.4%) with DGA Status 3 (critical condition), while only 246 transformers (17.3%) are classified as DGA Status 1 (normal condition) [61, 58, 76, 11]. Conversely, when using threshold values adapted for the Indonesian population, the distribution changes significantly with 774 transformers (54.4%) classified as DGA Status 1, and only 357 transformers (25.1%) identified as DGA Status 3 [52, 6, 96, 4]. A similar pattern is also observed in transformers with an O_2/N_2 ratio >0.2, where the North American standard

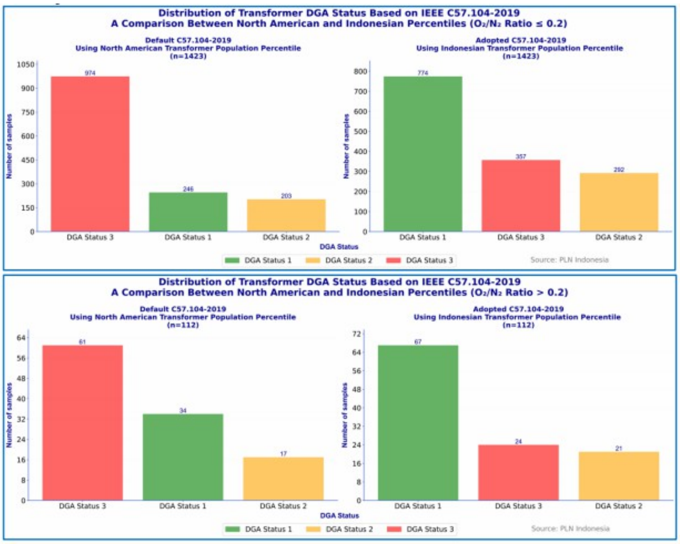

Figure 5. Comparison of DGA Status Distribution Based on IEEE C57.104-2019: North American Threshold Application versus Indonesian Adaptation Thresholds

threshold values classify 61 transformers (54.5%) as DGA Status 3, while with the adapted threshold values, only 24 transformers (21.4%) receive this status [71, 54, 85, 69]. This striking difference in distribution proves that the use of threshold values not adjusted to the local population can result in excessive false alarms or unnecessary maintenance actions [60, 35, 20, 65, 32, 62].

This significant difference underscores the importance of local adaptation of international standards, as direct application of threshold values from IEEE C57.104-2019 to Indonesian transformers can lead to inaccurate interpretations [49, 37, 26, 77, 55] . With much higher threshold values, many Indonesian transformers that are actually operating normally might be classified in higher DGA status (Status 2 or 3) if using North American standard threshold values [51, 53, 75, 67, 40] . Factors that may contribute to these differences include different operational environmental conditions such as higher ambient temperatures in Indonesia, different load characteristics, specific maintenance practices, and the possibility of differences in the composition of mineral oil and insulation materials used in transformers in both geographical regions [1, 13, 65, 2, 41, 70]. The results of this study affirm the importance of developing threshold values based on local transformer population characteristics to improve diagnostic accuracy and reliability of DGA result interpretation [33, 38, 83, 94, 97, 23].

4.3 Multi-Method Fault Identification Implementation Result

4.3.1 Fault Identification Using Duval Triangle 1

The implementation of the Duval Triangle 1 method on 1535 DGA data samples from the Indonesian transformer population resulted in a significant distribution of failure identifications, as shown in Fig. 6 [8, 63, 22, 64, 98]. Analysis based on DGA

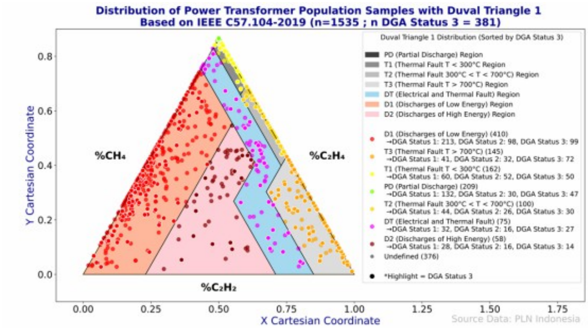

Figure 6. Distribution of Power Transformer Population Samples with Duval Triangle 1 Based on IEEE C57.104-2019 (n=1535; n DGA Status 3 = 381) [35, 68, 92, 43]

Status shows that of the 410 D1 cases, 213 were at DGA Status 1, 98 at DGA Status 2, and 99 at DGA Status 3, indicating that D1 type failures can occur at various severity levels [60, 33, 79, 61, 15, 77, 56] . A similar pattern was also observed in other failure types, with the highest percentage of DGA Status 3 cases found in T3 type failures (49.7%), showing a strong correlation between high-temperature thermal failures and higher severity levels [1, 91, 14, 40, 17, 39, 99]. The distribution of data points on Duval Triangle 1 shows clear clustering in the D1, PD, and T1 zones, providing visual confirmation of the prevalence of these failure types in the Indonesian transformer population[74, 48, 54, 72, 100, 31, 19, 50, 98].

4.3.2 Fault Identification Using Duval Triangle 4

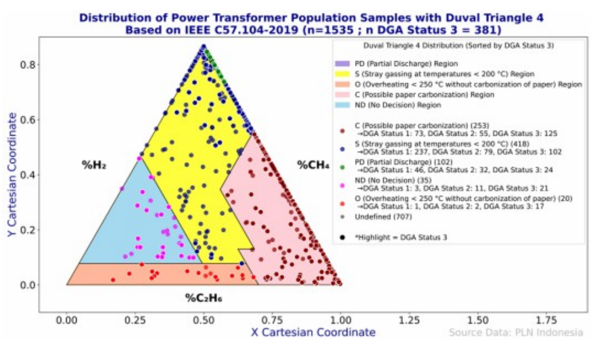

Figure 7. Distribution of Power Transformer Population Samples with Duval Triangle 4 Based on IEEE C57.104- 2019 (n=1535; n DGA Status 3 = 381)

The implementation of the Duval Triangle 4 method on the Indonesian transformer population resulted in a significant distribution of failure identification, as shown in Fig. 7 [8, 63, 4, 64, 50]. Analysis based on DGA Status showed that of the 418 Stray gassing cases, 237 were at DGA Status 1, 79 at DGA Status 2, and 102 at DGA Status 3 [74, 79, 34, 43, 12]. Meanwhile, of the 253 Possible paper carbonization cases, the distribution showed 73 cases at DGA Status 1, 55 at DGA Status 2, and 125 at DGA Status 3, indicating that paper carbonization correlates with higher severity levels [8, 5, 40, 41, 59]. The distribution of samples on Duval Triangle 4 revealed a significant concentration in zone S at the top of the triangle, while zone C was dominated by samples with DGA Status 3, indicating that failures involving degradation of paper insulation tend to have more serious severity levels in the Indonesian transformer population [1, 33, 52, 61, 15, 56, 10].

4.3.3 Fault Identification Using Duval Triangle 5

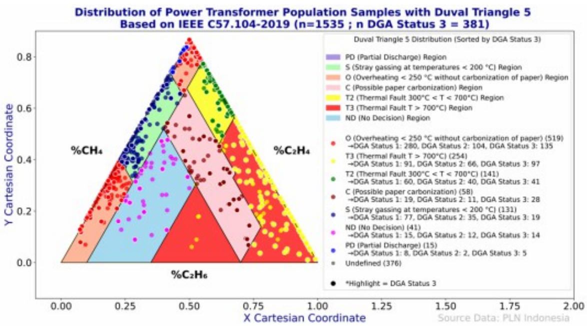

Figure 8. Distribution of Power Transformer Population Samples with Duval Triangle 5 Based on IEEE C57.104- 2019 (n=1535; n DGA Status 3 = 381)

The implementation of the Duval Triangle 5 method on the Indonesian transformer population, as shown in Fig. 8, resulted in a significant distribution of failure identification from a total of 1535 DGA data samples [8, 63, 22, 98]. Analysis based on DGA Status showed that of the 519 Overheating cases, there was a distribution of 280 cases at DGA Status 1, 104 cases at DGA Status 2, and 135 cases at DGA Status 3 [60, 79, 32, 61, 43]. A similar pattern was observed in T3 failures with 91 cases at DGA Status 1, 66 at DGA Status 2, and 97 at DGA Status 3 [24, 76, 4, 47, 50] .The distribution of samples on the triangle showed a significant concentration in zones O and T3, while zone C had fewer sample distributions but with a relatively high proportion for DGA Status 3, indicating that paper carbonization in Indonesian transformers tends to correlate with higher severity levels [35, 5, 3, 6, 40, 41, 57].

4.3.4 Fault Identification Using Duval Pentagon 1

The implementation of the Duval Pentagon 1 method on the Indonesian transformer population, as shown in Fig. 9, resulted in significant failure identification from a total of 1535 samples [8, 22, 64] . Analysis based on DGA Status showed that of the 605 D2 cases, the majority (414 cases) were at DGA Status 1, while only 92 cases were identified as DGA Status 3 [79, 61, 34, 43]. In contrast, T3 failures showed a higher proportion of DGA Status 3 with 23 out of 68 cases (33.8%) [36, 24, 101, 40]. The distribution of samples on the pentagon showed significant concentration in zones D2 and S, with DGA Status 3 points (marked with highlight color) tending to concentrate near the center of the pentagon and along the D1 and T3 zones, indicating

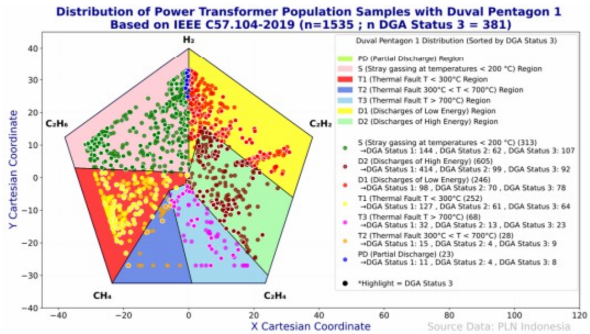

Figure 9. Distribution of Power Transformer Population Samples with Duval Pentagon 1 Based on IEEE C57.104- 2019 (n=1535; n DGA Status 3 = 381)

a correlation between position on the pentagon and failure severity level [51, 91, 71, 21, 82].

4.3.5 Fault Identification Using Duval Pentagon 2

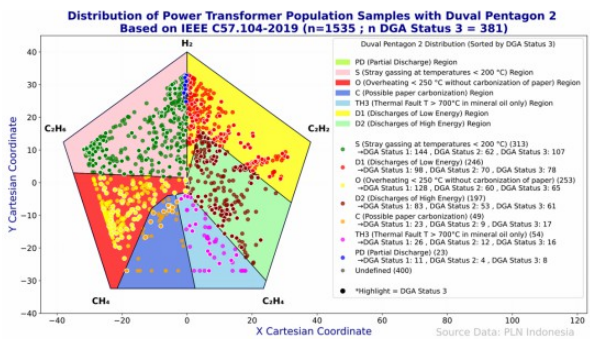

Figure 10. Distribution of Power Transformer Population Samples with Duval Pentagon 1 Based on IEEE C57.104- 2019 (n=1535; n DGA Status 3 = 381)

The implementation of the Duval Pentagon 2 method on the Indonesian transformer population, as shown in Fig. 10, resulted in a more specific distribution of failure identification for failure sub-types from a total of 1535 DGA data samples [8, 63, 22, 64] . Analysis based on DGA Status showed that of the 313 S cases, there were 144, 62, and 107 cases for DGA Status 1, 2, and 3 respectively [79, 34, 43, 18]. Meanwhile, of the 49 C cases, the proportion of DGA Status 3 was higher with 17 cases (34.7%), indicating a correlation between paper carbonization and more serious severity levels [60, 8, 5, 40, 61] . The distribution of data points on the pentagon showed different concentrations for each failure category, with DGA Status 3 points (marked in black) concentrated along the D2, C, and TH3 zones, which is consistent with the characteristics of high-energy failures in power transformers in Indonesia [35, 37, 32, 6, 85, 4].

4.4 Correlation Analysis Between Gas Parameters and Normalized Energy Intensity

Pearson correlation analysis between dissolved gas concentrations and NEI (Normalized Energy Intensity) values reveals significant differences in correlation patterns based on the O_2/N_2 ratio [1, 14, 32, 61, 57] . For transformers with an O_2/N_2 ratio >0.2, NEI Oil Fig. 11 shows the highest positive correlation with ethylene (C_2H_4) at 0.976, followed by hydrogen (H_2) at 0.745, acetylene (C_2H_2) at 0.709, ethane (C_2H_6) at 0.680, and TDCG at 0.895 [35, 36, 91, 53, 43] . Meanwhile, NEI Paper Fig. 12 strongly correlates with carbon monoxide (CO) at 0.934 and carbon dioxide (CO_2) at 0.446 [8, 20, 40, 41, 59]. Different correlation patterns were found in transformers with an O_2/N_2 ratio $\leq$0.2, where NEI Oil correlates most strongly with methane (CH_4) at 0.845, followed by ethylene (C_2H_4) at 0.877, ethane (C_2H_6) at 0.598, and acetylene (C_2H_2) at 0.576, with an average correlation coefficient of 0.316, lower than transformers with an O_2/N_2 ratio >0.2 (0.435) [63, 48, 101, 21, 76, 39] .

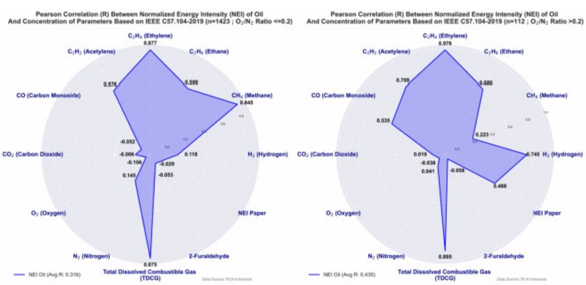

Figure 11. Pearson Correlation (R) Between Normalized Energy Intensity (NEI) of Oil and Concentration of Parameters Based on IEEE C57.104-2019 (n=1423; O_2/N_2 Ratio $\leq$0.2, n=112; O_2/N_2 Ratio >0.2)

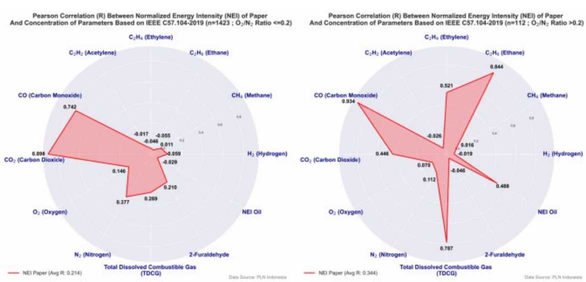

Figure 12. Pearson Correlation (R) Between Normalized Energy Intensity (NEI) of Paper and Concentration of Parameters Based on IEEE C57.104-2019 (n=1423; O_2/N_2 Ratio $\leq$0.2, n=112; O_2/N_2 Ratio >0.2)

In Fig. 13, correlations between gas ratios and NEI Oil show much lower correlation values compared to absolute gas concentrations, with the highest correlation value only reaching 0.281 for the CH_4/H_2 ratio [45, 102, 6] [45, 102, 6]. This pattern is consistent across all evaluated gas ratios (C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6, CO_2/CO), indicating that gas ratios are less effective as failure severity indicators compared to absolute gas concentrations [103, 65, 56]. Correlations between gas ratios and NEI Paper, with the correlation value only reaching 0.071 for the CO_2/CO

ratio [33, 62, 12]. Although this ratio is theoretically related to paper degradation, the relatively low correlation indicates that absolute CO concentration (with R=0.934) is a much better indicator for evaluating paper insulation condition compared to the CO_2/CO ratio [60, 67, 4] .

The strong positive correlation of Gas Conc – NEI compared to Gas Ratio – NEI indicates that DGA interpretation methods using absolute concentrations (such as Duval Triangle and Duval Pentagon) may be more reliable than methods using gas ratios (such as Rogers Ratio, IEC60599 Ratio and Doernenburg Ratio) [51, 26, 22] . This finding is in line with the trend in IEEE C57.104-2019 standard which places more emphasis on approaches based on absolute gas concentrations and percentile values [79, 43, 99] .

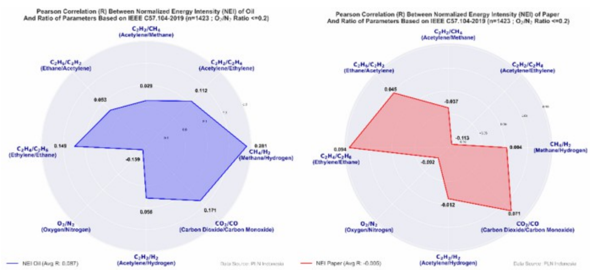

Figure 13. Pearson Correlation (R) between Gas Ratios and Normalized Energy Intensity (NEI) Values for both Oil and Paper in Indonesian Transformer Population (n=1423; O_2/N_2 Ratio $\leq$0.2)

4.5 Multi-Method Fault Identification Validation Using Normalized Energy Intensity

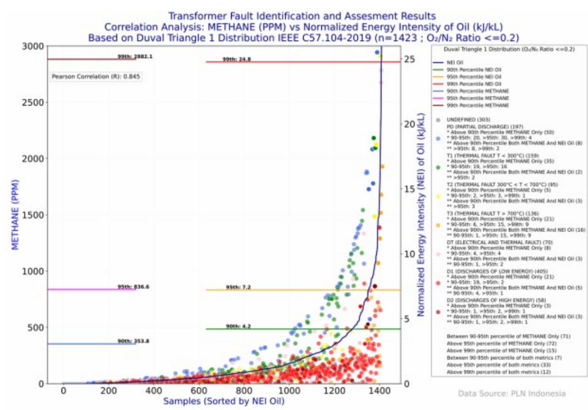

Figure 14. Pearson Correlation Analysis (R=0.845) between Normalized Energy Intensity (NEI) Oil and Methane (CH_4) Concentration Based on Duval Triangle 1 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Methane as a Leading Indicator for Fault Types PD and T1

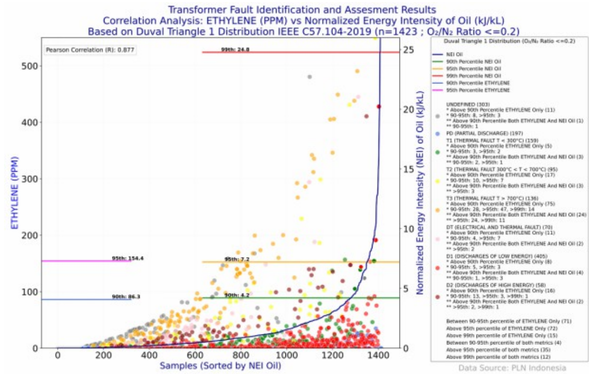

Figure 15. Pearson Correlation Analysis (R) between Normalized Energy Intensity (NEI) Oil and Ethylene (C_2H_4) Concentration Based on Duval Triangle 1 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Ethylene as a Leading Indicator for Fault Types T3 and DT

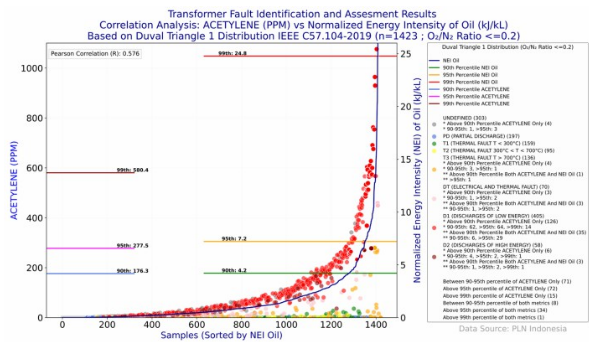

Figure 16. Pearson Correlation Analysis (R=576) between Normalized Energy Intensity (NEI) Oil and Acetylene (C_2H_2) Concentration Based on Duval Triangle 1 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Acetylene as a Leading Indicator for Fault Type D1

4.6 Effectiveness of Transformer Failure Identification Methods Based on Key Gas After Optimization Using DGA Status 3 and Above 95th Percentile Key Gas & NEI Oil

(a) Methane Distribution (CH_4, n=33) shows highest effectiveness for PD failure identification with DTM1 and S with DPM1 [8, 63, 6]; (b) Ethane Distribution (C_2H_6, n=25) shows highest effectiveness for C failure identification with DTM4 and DTM5 [8, 36, 91]; (c) Ethylene Distribution (C_2H_4, n=35) shows highest effectiveness for T3 failure identification with DTM1 confirmed by highest correlation (R=0.877) with NEI Oil [1, 14, 56]; (d) Acetylene Distribution (C_2H_2, n=35) shows highest effectiveness for D1 failure identification with DTM1 and D2 with DPM1 [21, 4, 22].

The effectiveness analysis results of transformer failure identification methods based on key gases after optimization using DGA Status 3 and gas concentrations above the 95th percentile and NEI Oil values show significant consistency patterns for various types of failures [1, 36, 14] . Based on data displayed in Fig. 23 (a), methane (CH_4) with sample size n=33 shows high effectiveness in identifying PD (Partial

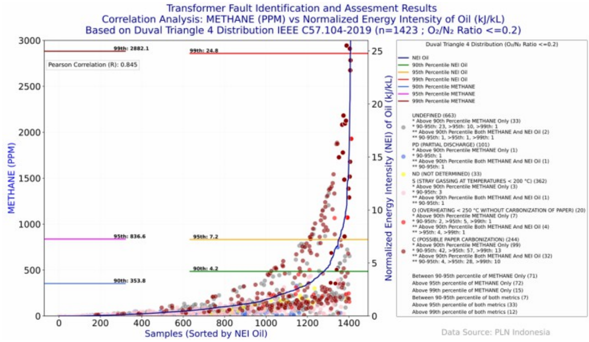

Figure 17. Pearson Correlation Analysis (R=0.845) between Normalized Energy Intensity (NEI) Oil and Methane (CH_4) Concentration Based on Duval Triangle 4 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Methane as a Leading Indicator for Fault Type C (Possible Paper Carbonization)

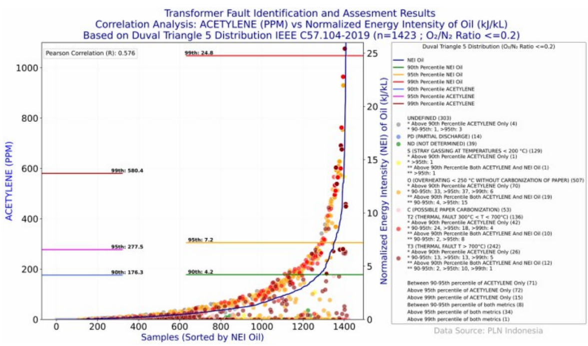

Figure 18. Correlation Analysis (R=0576) between Normalized Energy Intensity (NEI) Oil and Acetylene (C_2H_2) Concentration Based on Duval Triangle 5 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Acetylene as a Leading Indicator for Fault Types T2 and O

Discharge) type failures using the DTM1 method and S (Stray gassing) type failures using the DPM1 method, where the highest concentration is seen in the S zone with 12 identified cases [8, 63, 22]. Meanwhile, Fig. 23 (b) displays the distribution of ethane (C_2H_6) with sample size n=25 which effectively identifies C (Carbonization) type failures using DTM4 (15 cases) and DTM5 (11 cases) methods [8, 36, 6]. For Fig. 23 (c), ethylene (C_2H_4) with n=35 shows excellence in identifying high-temperature thermal failures (T3) using the DTM1 method with 24 identified cases, which is also confirmed by the high correlation between ethylene and NEI Oil (R=0.877) [1, 14, 56]. In Fig. 23 (d), acetylene (C_2H_2) with n=35 shows the highest effectiveness in identifying D1 (Discharges of Low Energy) type failures using DTM1 (29 cases) and DPM1 (13 cases) methods [24, 63, 64] . The results of this multi-method analysis confirm that each key gas has specific advantages in identifying certain types of failures, with methane being the best indicator for PD and S, ethane for C, ethylene for T3, and acetylene for D1 and D2, so that a multi-method approach with an optimized key gas combination produces more accurate and comprehensive transformer failure

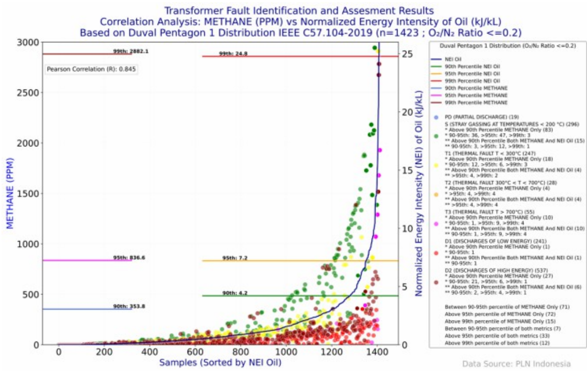

Figure 19. Pearson Correlation Analysis (R=0.845) between Normalized Energy Intensity (NEI) Oil and Methane (CH_4) Concentration Based on Duval Pentagon 1 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Methane as a Leading Indicator for Fault Type S (Stray Gassing)

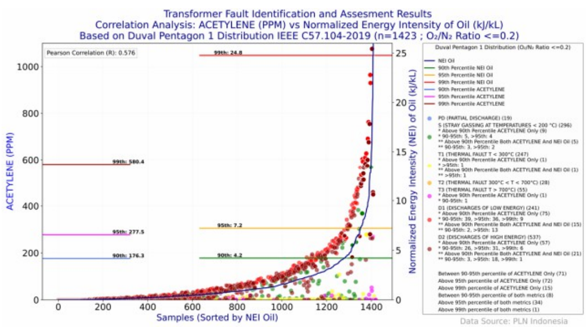

Figure 20. Pearson Correlation Analysis (R=0.576) between Normalized Energy Intensity (NEI) Oil and Acetylene (C_2H_2) Concentration Based on Duval Pentagon 1 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming Acetylene as a Leading Indicator for Fault Type D2 (Discharges of High Energy)

diagnoses [35, 38, 39] .

4.7 Consistency Analysis and Multi-Method Optimization of Power Transformer Failure Identification Based on IEEE C57.104-2019

The correlation analysis results of TDCG parameters and carbon gases (CO, CO_2) against NEI Oil and NEI Paper reveal inconsistencies in fault type patterns across all Duval Triangle and Pentagon interpretation methods [35, 51, 21] . In Fig. 21, it can be seen that Although carbon monoxide (CO) shows a strong correlation with NEI Paper (R=0.742), the fault type distribution pattern does not show clear clustering across various Duval methods [8, 36, 63]. This contrasts with hydrocarbon gases such as methane (CH_4) which shows significant fault type pattern consistency with NEI Oil (R=0.845) across all Duval methods [1, 38, 32] . Fig. 22 confirms that TDCG does not show consistency in fault type patterns against NEI Oil and NEI Paper across all Duval Triangle and Pentagon methods, with trend patterns that tend to lag behind NEI [95, 35, 48]. These findings confirm that the TDCG method only

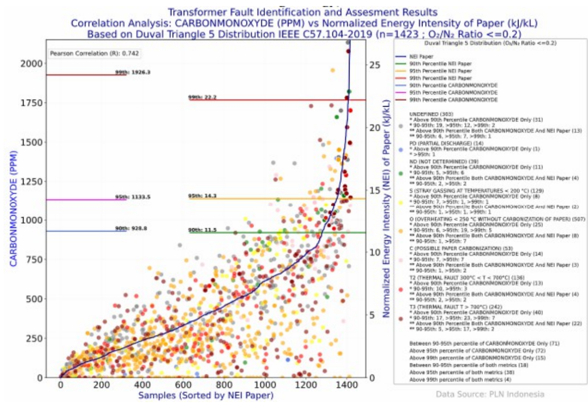

Figure 21. Pearson Correlation Analysis (R=0.742) between Normalized Energy Intensity (NEI) Paper and Carbon Monoxide (CO) Concentration Based on Duval Triangle 5 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming the Absence of Fault Type Pattern Consistency Despite Strong Correlation

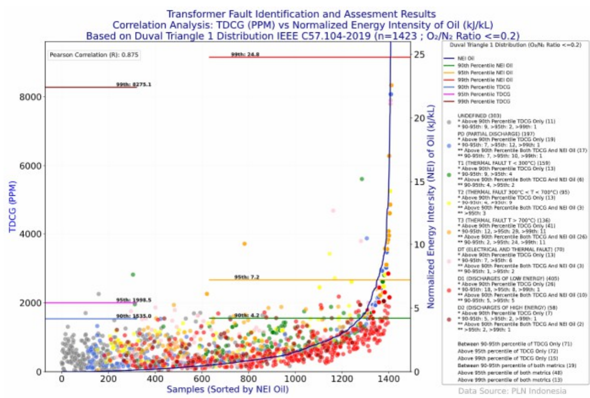

Figure 22. Pearson Correlation Analysis between Normalized Energy Intensity (NEI) Oil and TDCG Concentration Based on Duval Triangle 1 Distribution (n=1423; O_2/N_2 Ratio $\leq$0.2) Confirming the Absence of Fault Type Pattern Consistency with Trends Tending to Lag Behind NEI

focuses on the total value of combustible gases dissolved in transformer oil without considering in-depth interpretation of failure types [13, 53, 52], while the transition from TDCG to NEI reflects a paradigm shift in transformer diagnosis from a simple gas concentration-based approach toward a more comprehensive thermochemical energy-based approach [1, 14, 40].

A more in-depth analysis of Table 4 demonstrates the consistency of trending severity patterns with similar failure types between key gases and NEI Oil across various fault type codes [35, 8, 26]. For Partial Discharge (PD), the combination of Methane with DTM 1 method shows the best consistency [103, 36, 63]. For Thermal Fault T < $300°C$ (T1), the combinations of Methane and Ethane with DTM 1, as well as Methane with DPM 1, demonstrate strong consistency [63, 22, 64] . For Thermal Fault $300°C$ < T < $700°C$ (T2), Acetylene with DTM 5 becomes the best combination

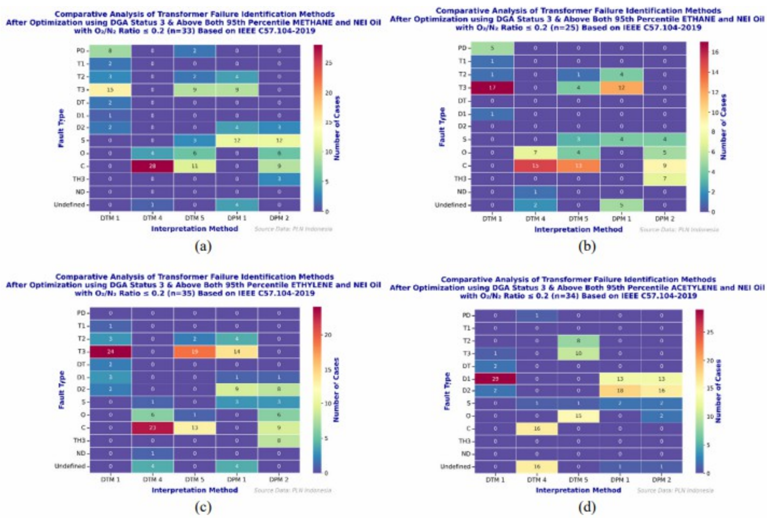

Figure 23. Effectiveness of Transformer Failure Identification Methods Based on Key Gas After Optimization Using DGA Status 3 and Gas Concentration Above 95th Percentile and NEI Oil:

Table 4. Consistency of Key Gas Trending Patterns Compared to NEI Oil Across Various Interpretation Methods with Similar Fault Types

Fault Type	Duval Triangle 1				Duval Triangle 4				Duval Triangle 5				Duval Pentagon 1				Duval Pentagon 2			
	Methane	Ethane	Ethylene	Acetylene	Methane	Ethane	Ethylene	Acetylene	Methane	Ethane	Ethylene	Acetylene	Methane	Ethane	Ethylene	Acetylene	Methane	Ethane	Ethylene	Acetylene
PD	✓																			
T1	✓	✓												✓						
T2												✓								
T3			✓								✓	✓			✓					
DT			✓																	
D1				✓												✓				✓
D2																✓				✓
S						✓		✓	✓	✓			✓				✓			
O									✓	✓		✓						✓		
C					✓			✓												
TH3																			✓	
ND						✓				✓										

[8, 63, 50]. For Thermal Fault T > 700°C (T3), trending pattern consistency appears dominant in the combination of Ethylene with DTM 1 and DTM 5 [8, 104, 50] . For Electrical and Thermal Fault (DT), Discharges of Low Energy (D1), and Discharges of High Energy (D2), there are variations of consistency patterns that are prominent in certain gas and method combinations [35, 63, 22]. For example, Acetylene with DTM 1 and DPM 2 for D1, along with other combinations for fault types S (Stray gassing at temperatures < 200°C), O (Overheating < 250°C without carbonization of paper), C (Possible paper carbonization), TH3 (Thermal Fault T > 700°C in mineral oil only), and ND (Not Determined) [21, 68, 50]. These findings emphasize the importance of implementing a multi-method approach in identifying power transformer failures, where combinations of key gases and interpretation methods need to be specifically adjusted to the type of failure that occurs [36, 20, 68].

Consistency analysis of transformer failure identification methods based on key gas correlation with NEI Oil yields significant findings as shown in Table 4. Research results reveal that the best failure identification method is the most effective and capable of consistently identifying failure types from low to high severity levels (NEI) [1, 14, 15] . Based on the displayed data, it is evident that each failure type has specific optimal key gases and interpretation methods [35, 38, 76].

The final synthesis of this research, as shown in Table 5, produces an optimized multi-method framework for power transformer failure identification based on Normalized Energy Intensity. This table summarizes the best diagnostic methods for each type of transformer failure by identifying key gases as leading indicators, best interpretation methods, severity indicators, and sensitivity levels [1, 8, 20] . The analysis results show that methane is the best leading indicator for PD, T1, S, and C type failures, with DTM1 as the optimal interpretation method for PD and T1, and DPM1 and DTM4 for S and C [36, 63, 22] . Meanwhile, ethylene proves to be the leading indicator for T3, DT, and TH3 failures, with DTM1 for T3 and DT, and DPM2 for TH3 [6, 21, 64]. Acetylene shows the highest effectiveness for D1, D2, T2, and O failures, with the highest sensitivity for D1 failures (29 cases) and T3 failures (24 cases) [8, 48, 17]. NEI Oil consistently becomes the best severity lagging indicator for all types of failures, confirming the superiority of the absolute concentration-based approach compared to gas ratio-based methods [14, 15, 56] . This synthesis provides comprehensive guidance for practitioners to optimize the power transformer failure diagnosis process by selecting the most appropriate combination of key gases and interpretation methods for each type of failure [32, 61, 68].

Table 5. Optimized Multi-Method Framework for Power Transformer Failure Identification Based on Normalized Energy Intensity According to IEEE C57.104-2019 Showing the Best Key Gas as Leading Indicator, Best Interpretation Method, Best Severity Indicator, and Sensitivity Level for Each Type of Failure [1, 14, 32]

Fault Type Identification	Best Key Gas Leading Indicator	Best Interpretation Method	Best Severity Lagging Indicator	Sensitiveness
PD	Methane	DTM1	NEI Oil	8
T1	Methane	DTM1	NEI Oil	2
T2	Acetylene	DTM5	NEI Oil	8
T3	Ethylene	DTM1	NEI Oil	24
DT	Ethylene	DTM1	NEI Oil	2
D1	Acetylene	DTM1	NEI Oil	29
D2	Acetylene	DPM1	NEI Oil	18
S	Methane	DPM1	NEI Oil	12
O	Acetylene	DTM5	NEI Oil	15
C	Methane	DTM4	NEI Oil	28
TH3	Ethylene	DPM2	NEI Oil	8
ND	Ethane	DTM5	NEI Oil	

4.8 Limitations and Regional Adaptability of the Multi-Method Framework

Although the NEI-based multi-method framework in this research has proven effective for the Indonesian transformer population, it is important to understand its limitations in the context of global application. This framework was developed based on a dataset of 1525 DGA samples from PLN Indonesia transformers operating in tropical environmental conditions with high temperature and humidity, specific load patterns, and certain maintenance practices that may differ from other regions [13, 20, 14]. To adapt this methodology to other geographical regions, several adjustments are needed including: determination of new percentile threshold values based on representative local datasets, data stratification based on O_2/N_2 ratio and transformer age according to local population characteristics [1, 60, 32], and evaluation of correlations between dissolved gases and NEI values that may vary depending on the composition of mineral oil and insulation materials used [32, 40, 41]. Factors such as climate differences, network load, and maintenance policies also need to be considered as they can influence gas formation patterns and DGA result interpretation [51, 37, 61] , so the methodology must be flexible enough to accommodate these variations while maintaining a consistent diagnostic framework [35, 38, 39].

4.9 Alternative Analysis Methods Beyond Pearson Correlation

Although Pearson correlation analysis has provided valuable insights into the relationship between dissolved gas concentrations and NEI values, this method has limitations in revealing non-linear and complex relationships that may exist in DGA data [33, 38, 39]. Several recent studies have applied more sophisticated multivariate analysis methods for DGA interpretation [6, 61, 94] . Taha et al. (2021) used Principal Component Analysis (PCA) to identify hidden patterns in DGA data and improve diagnostic accuracy [32, 23, 84]. Son et al. (2023) compared various machine learning methods such as Decision Tree, Support Vector Machine, and MultiLayer Perceptron, with results showing that MLP provides the highest accuracy reaching 94% for transformer failure identification [74, 77, 30] . Meanwhile, Gopakumar and Raja (2023) developed a fuzzy logic model that integrates DGA interpretation, gas levels, and gas formation rates for transformer failure severity evaluation with accuracy levels reaching 98.8% [33, 36, 15] . These advanced methods have the potential to reveal more complex patterns and relationships between DGA parameters and transformer conditions [76, 4, 105] and can be a direction for future research to improve the accuracy of transformer failure diagnosis in Indonesia[13, 52, 67] .

4.10 Practical Applications and Implementation

This research has significant practical applications for power transformer condition monitoring systems in Indonesia, with direct implementation in the form of a web-based decision support system that integrates the multi-method framework and adjusted percentile threshold values [60, 36, 6]. This system allows PLN engineers and technicians to input dissolved gas concentration data or acquire data from DGA Online Monitoring to obtain comprehensive analysis of transformer conditions, including identification of failure types and their severity levels [66, 94, 4]. As shown in the research results, using threshold values adjusted to Indonesian transformer characteristics reduces the number of transformers classified as DGA Status 3 (critical condition) from 68.4% to only 25.1%, resulting in a more proportional and realistic DGA status distribution [13, 2, 34]. Implementation of this framework in PLN's condition monitoring system will optimize condition-based maintenance programs by reducing false alarms and allocating maintenance resources more efficiently to transformers that truly require immediate attention [33, 32, 77]. Correlation analysis results showing strong relationships between ethylene (R=0.877) and methane (R=0.845) with NEI Oil have also been integrated into the system's diagnostic algorithm, providing more accurate indications of transformer failure severity [1, 14, 56] . In the long term, this framework will become the basis for developing national standards for DGA interpretation tailored to Indonesian transformer characteristics, providing benefits not only for PLN but also for the Indonesian electricity industry as a whole [27, 40, 68] .

5. Conclusion

Based on research conducted on power transformer failure identification optimization with a multi-method approach based on Normalized Energy Intensity (NEI) according to IEEE C57.104-2019 standards, adapted for Indonesian transformer characteristics, it can be concluded that dissolved gas characteristics in the power transformer population in Indonesia show significant differences compared to the transformer population used in developing IEEE C57.104-2019 standards, with key gas concentrations such as H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2 at the 90th, 95th, and 99th percentiles in Indonesia consistently higher than North American references. This diagnostic framework provides failure severity validation previously unavailable in conventional DGA methods, resulting in consistent fault type patterns from low to high severity levels. This research has successfully established threshold values for dissolved gas concentrations based on the 90th, 95th, and 99th percentiles specific to the Indonesian transformer population, which have proven to result in more proportional and realistic DGA status distributions, thus reducing false alarms and improving the effectiveness of conditionbased maintenance programs. There are very strong positive correlations between hydrocarbon gas concentrations (especially ethylene and methane) with NEI Oil values, and between carbon monoxide and NEI Paper, with ethylene being the main indicator of high-temperature thermal failures with the highest correlation (R=0.877), while methane (R=0.845) becomes the most consistent indicator across all interpretation methods. Comparative analysis shows that each DGA interpretation method (Duval Triangle 1, 4, 5 and Duval Pentagon 1, 2) has specific advantages depending on the type of failure and key gases involved, where the optimized multimethod approach combining key gas concentrations above the 95th percentile and high NEI Oil has proven to provide the most accurate and comprehensive diagnosis. The NEI-based multimethod framework and local percentile thresholds developed in this research are adaptive to transformer characteristics in Indonesia, capable of providing more accurate diagnosis, reducing the risk of catastrophic failures, and can be directly implemented by national electrical utilities to improve the reliability of condition monitoring systems.

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