

Analysis of GT 2.1 Transformer Oil Testing using the Dissolved Gas Analysis (DGA) Method at PT PLN Nusantara Power

Amsal Aritonang¹, Soni Prayogi^{2✉}

^{1,2} Teknik Elektro, Fakultas Teknologi Industri, Universitas Pertamina, Indonesia

✉ **Corresponding Author** : Soni Prayogi (e-mail: soni.prayogi@universitaspertamina.ac.id)

Article Information	ABSTRACT
Article History Received : January 16, 2025 Revised : January 21, 2025 Published : January 30, 2025	This study analyzes transformer oil from the GT 2.1 transformer at PT PLN Nusantara Power using the Dissolved Gas Analysis (DGA) method. Transformers are crucial for power systems, and their performance relies on the condition of their oil, which acts as both an insulator and a coolant. The DGA method detects gases like hydrogen, methane, ethylene, ethane, and acetylene in the oil, which indicate electrical or thermal faults. Oil samples were analyzed using diagnostic techniques such as the Rogers ratio, Duval triangle, and IEC standards to assess potential faults. The results revealed faults like thermal overheating and electrical discharges, offering valuable insights into the transformer's health. The study highlights the importance of routine oil testing and DGA for predictive maintenance, enabling early fault detection. This proactive approach helps prevent failures, reduces outages, and extends transformer lifespan, ultimately enhancing the reliability and efficiency of power delivery at PT PLN Nusantara Power. The findings support the integration of advanced diagnostic methods in maintaining critical electrical infrastructure.
Keywords: <i>DGA;</i> <i>Gas Chromatography;</i> <i>Insulating Oil;</i> <i>Transformer.</i>	

INTRODUCTION

The transformer is an essential component in the electricity distribution and transmission system, whose function is to change the electric voltage to a level more suitable for distribution and end use (Thomas et al., 2014). Transformers ensure that electrical energy can be transmitted efficiently from power plants to end consumers, over extensive and complex electrical networks (Wu et al., 2020). In this process, the transformer must be able to withstand varying electrical loads and maintain optimal performance under different operational conditions (Taha et al., 2016). The reliability of a transformer is very dependent on the condition of the insulating material used in it (Marzuki et al., 2023), one of which is insulating oil (Kang et al., 2023). Transformer oil not only functions as an electrical insulator, but also acts as a cooling medium to remove heat generated during operation (Abu-Siada & Hmood, 2015). However, over time, this oil can experience degradation caused by factors such as heat, electrical stress, and contamination, which can ultimately affect the performance and reliability of the transformer (Abdo et al., 2021).

One of the most effective methods for monitoring the condition of transformer oil is through Dissolved Gas Analysis (DGA) (D. Yang et al., 2022). The DGA method involves taking oil samples and analyzing dissolved gases resulting from oil degradation due to thermal and electrical phenomena in the transformer (Han et al., 2023). The gases analyzed include hydrogen, methane, ethane, ethylene, and acetylene, each of which can indicate certain types of damage such as over-heating, partial discharge, and arcing (Faiz & Soleimani, 2018). The concentrations and ratios of these gases provide important diagnostic clues for assessing transformer condition and

determining necessary maintenance measures (X. Yang et al., 2019). DGA has been recognized as a very useful tool for early detection of potential problems in transformers (Muhammad et al., 2023), allowing timely intervention before more serious and expensive failures occur (Shanker et al., 2017). The monitoring method used previously in the analysis of GT 2.1 transformer oil at PT PLN Nusantara Power generally relied on visual inspection, measurement of physical parameters such as color, viscosity, and other conventional tests that have limitations in early detection of degradation or internal disturbances in the transformer. As a development, the DGA method is offered as a more accurate and diagnostic approach in detecting and analyzing dissolved gases in transformer oil produced due to insulation degradation or electrical failure. With the DGA method, early identification of potential damage such as overheating, partial discharge, or electrical faults can be carried out more effectively, thereby increasing the reliability and service life of the transformer through predictive maintenance based on dissolved gas data.

The main objective of this research is to develop a monitoring method that can detect early signs of damage or degradation in transformers to prevent more severe damage and minimize the risk of power outages. The contribution of this research is to provide deeper insight into the use of DGA as a reliable diagnostic tool in the electrical industry, as well as providing practical guidance for the interpretation of DGA results in the context of predictive maintenance. The novelty of this research lies in the more detailed analytical approach and real case studies, which demonstrate the effectiveness of DGA in various operational situations. Thus, this research not only strengthens the validity of DGA as a diagnostic method but also proposes implementation strategies that can improve electrical transformers' reliability and operational efficiency (Wajid et al., 2023). It is hoped that the results of this analysis will provide deeper insight into the condition of the transformer and potential problems that may occur (Ramadhan et al., 2023). With this information, PT PLN Nusantara Power can develop more effective predictive maintenance strategies, improving transformer reliability and longevity and overall operational efficiency (Taha et al., 2017). Through this research, it is hoped that it can significantly contribute to efforts to increase the reliability of the electricity distribution system and reduce the risk of transformer failure in the future.

RESEARCH METHODS

The DGA technique method is commonly used to monitor transformer conditions by analyzing gases dissolved in transformer insulating oil. This research will combine qualitative and quantitative analysis of gas dissolved in transformer oil to determine transformer operational conditions, identify potential damage or failure, and provide recommendations for necessary maintenance or action (Ali et al., 2023). Furthermore, to ensure optimal performance and reliability. By utilizing qualitative and quantitative approaches, this study aims to improve the accuracy of fault diagnosis by identifying gas composition patterns and correlating them with specific failure modes. The analysis will be conducted using established interpretation methods such as the Gas Key Method, Duval's Triangle, and Roger's Ratio to classify potential faults, including overheating, partial discharges, and arcing. The findings of this study will contribute to more effective predictive maintenance strategies, minimizing unexpected transformer failures and improving the overall efficiency of power system operations.

This electric current is distributed through the distribution network for use by homes, industries, and businesses around the PT PLN Nusantara Power area as seen in Figure 1. This research method will involve taking regular transformer oil samples from the GT 2.1 transformer at PT PLN Nusantara Power, followed by dissolved gas analysis using equipment and techniques that comply with industry standards with periodic sampling every 3 or 6 months to ensure consistent monitoring of the transformer's health. The GT 2.1 transformer, which is in operation, plays an important role in maintaining the stability of the electricity supply in the distribution network.

Furthermore, this research will combine quantitative and qualitative approaches in dissolved gas analysis to gain a comprehensive understanding of transformer conditions (Cheng &

Yu, 2018). Quantitative analysis will involve measuring the concentration of certain gases in the transformer oil, such as *methane* (CH_4), *ethane* (C_2H_6), *ethylene* (C_2H_4), *acetylene* (C_2H_2), and *hydrogen* (H_2), which can provide clues about potential damage or failure in the transformer (Ngwenyama & Gitau, 2024). Meanwhile, qualitative analysis will include identifying patterns of dissolved gases in transformer oil to determine possible causes of these gases, such as poor lubrication, discharge, or leaks, which may affect transformer performance (Luo et al., 2020). This research method will also focus on environmental and operational factors influencing the analysis results, such as temperature, pressure, and transformer operational load. Thus, it is hoped that this research can increase the operational efficiency and service life of GT 2.1 transformers at PT PLN Nusantara Power through a better understanding of the condition and maintenance required.

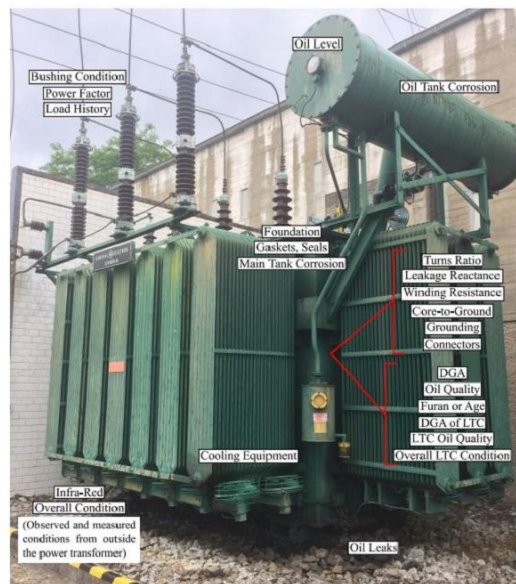


Figure 1. Schematic of the PT PLN Nusantara Power PLTGU cycle

RESULTS AND DISCUSSION

PT PLN Nusantara Power Generation System

PT PLN Nusantara Power operates an efficient and sustainable electricity generation cycle. The process begins with introducing natural gas as the main fuel into the combustion furnace. Natural gas is burned with air in the furnace to produce high heat. This heat is then used to heat water in a closed system, turning it into steam as seen in Figure 2. The steam produced has high pressure and is passed through a turbine, which rotates quickly due to the pressure of the steam ("Distributed Model Predictive Control," 2002). The turbine rotation is then used to drive an electric generator, producing electric current through electromagnetic induction (Wang et al., 2021). Meanwhile, the remaining heat from the combustion process and steam formation is cooled through a cooling system to maintain stability. This process occurs continuously, with routine maintenance and maintenance of all components and systems to ensure PT PLN Nusantara Power continues to operate optimally.

PT PLN Nusantara Power's PLTGU cycle is a combination of the Brayton cycle (gas cycle) with the Rankine cycle (steam cycle) and the HRSG boiler is part of the Rankine cycle. The process of the Brayton cycle consists of 4 stages, namely the Compression, Combustion, Expansion and Expenditure Stage. The first stage in the Brayton cycle is air compression. Air is taken from the environment and compressed to a higher pressure by the compressor. This compression increases air pressure and compresses it making it easier to produce efficient combustion. The second stage in the Brayton cycle is combustion (Kaur et al., 2022). The compressed air is then mixed with natural gas fuel in a combustion furnace. The combustion process produces high heat, which is used to heat the air and turn it into hot gas. The third stage

is Expansion. Hot gases from combustion flow into the turbine, where they pass through the turbine blades and cause them to spin. The kinetic energy from the rotation of the turbine is then converted into mechanical energy (Tra et al., 2019). The gas that has provided energy to the turbine is released into the environment as exhaust (Silviana & Prayogi, 2023). The cold gas will return to the beginning of the cycle and be taken back by the compressor to be compressed again.



Figure 2. PT PLN Nusantara Power Generation System

Dissolved Gas-In-Oil Analysis

The results of the analysis of gas in dissolved oil show how important the DGA method is in detecting and diagnosing various internal problems in electrical transformers. These results involve the analysis of gases such as hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), acetylene (C_2H_2), and carbon monoxide (CO) dissolved in transformer-insulating oil. Each of these gases indicates a specific type of damage. An increase in hydrogen concentration may indicate early decomposition of the oil or paper insulating material, while the presence of acetylene is often associated with arcing or electrical sparking within the transformer. A transformer showed a significant increase in hydrogen and acetylene concentrations as seen in Figure 3. This finding led to the diagnosis of internal arcing. Further inspection confirmed damage to the transformer's internal components caused by electrical sparks. This case highlights DGA's ability to detect critical problems at an early stage, allowing operators to take corrective action before the damage becomes more severe and causes total failure (Lopes et al., 2021). Under almost the same conditions it revealed an increase in ethylene and ethane, which indicates overheating of the oil components and insulating paper. This overheating was identified as a result of the continuous overload experienced by the transformer. Early identification of this problem allows for load reset and additional cooling to prevent further damage. These cases confirm the reliability of DGA in detecting various types of operational problems that can occur in transformers. This suggests that DGA can identify more subtle problems, such as slow but progressive degradation of insulating materials. For example, a gradual increase in carbon monoxide concentration indicates thermal degradation of the insulating paper. Continuous monitoring of these gases allows operators to track the condition of the insulation and plan maintenance or replacement before significant failure occurs.

The results of this study confirm that DGA is a very effective diagnostic tool for predictive maintenance of transformers. By identifying and monitoring the concentration of dissolved gases, operators can detect internal damage at an early stage, reducing the risk of sudden failure and extending the operational life of the transformer. Additionally, DGA provides significant economic advantages because the method is relatively inexpensive and does not require physical dismantling of the transformer, which can disrupt operations (SuganyaBharathi et al., 2013). Overall, the analysis results in this journal strengthen DGA's position as an important method in transformer maintenance and diagnostics. With proper implementation, DGA can increase

electrical system reliability, reduce maintenance costs, and prevent losses caused by transformer failure.

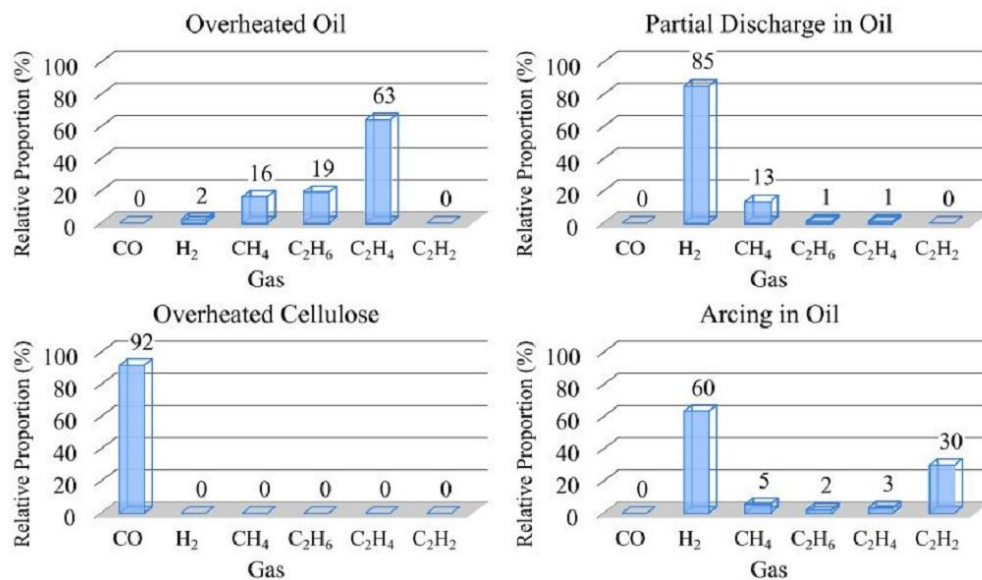


Figure 3. The key gas method is generated when insulation.

Dissolved Gas Analysis (DGA) Interpretation

The quality of transformer oil is very important and determines the life of the transformer. Problems that generally occur with transformer oil, such as moisture, greatly affect the ability of the dielectric oil in the short term and reduce the life of the transformer in the long term. The high acid content in transformer oil can accelerate the formation of sludge in the transformer and can reduce the oil's ability to act as a coolant (Nanfak et al., 2021). If the acid content in transformer oil is high, it can only be removed by a reclamation process. The acid can attack the metal in the tank and form more sludge. Acid can also damage the insulating paper and accelerate the degradation of the insulating paper. In extending the life of the transformer, it is very important to keep the transformer dry and free of oxygen. Moisture and oxygen can cause insulation paper to break down faster than normal and form acids, sludge, and more moisture (Maccartney et al., 2015). Sludge will stick to the winding and the inside of the structure, causing transformer cooling to be less efficient and run slowly, wasting a lot of time, and increasing the temperature. Acid causes an increase in the degradation process, which can form more acid, sludge, and moisture more quickly.

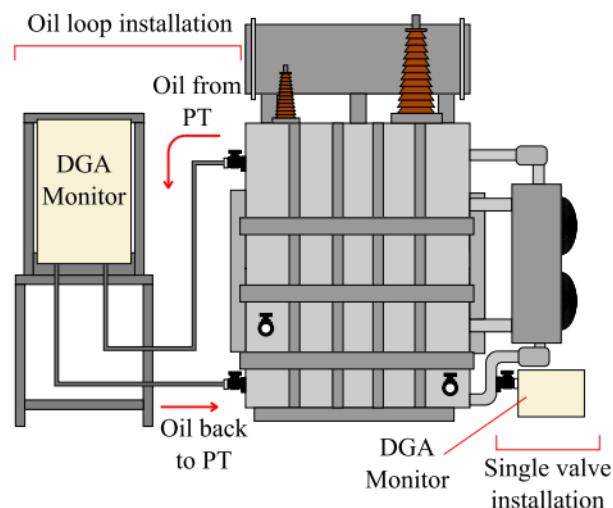


Figure 4. The valve locations in a power transformer and installation schematic

The interpretation standard for the Dissolved Gas Analysis test uses the latest standard IEEE C57.104-2019 which is a revision of the 2019 edition. Based on this standard, the condition of the transformer is seen based on the concentration of each gas as seen in Figure 4, a gas increase from the last 2 tests (Delta Gas) and gas increase value per year (Rate Gas) and divided into 4 conditions, namely: Status 1 (Normal Operation) Concentration of all gas is in low conditions, delta gas, and gas rate. Status 2 (Low Possibility of Interruption). Gas concentration in medium conditions, or gas delta. Status 3 (High Possibility of Interruption). Gas concentration in high or rate gas conditions. Extreme Status (Final Disturbance). Gas concentration in high, delta, or gas rate conditions. The following is data that has been tested in the PT PLN Nusantara Power laboratory which will be shown in Table 1.

Table 1. Dissolved gas in transformer oil by gas chromatography

Dissolved Gas Analysis of Transformer Oils by Gas Chromatograph (GC)										
Sampling Date	25/10/20	29/09/21	24/03/22	10/10/22	17/04/23	27/10/23	Gassing Concentration Limit			
Received Date	25/10/20	30/09/21	25/03/22	10/10/22	17/04/23	27/10/23	IEEE C57.104-2019			
Test Date	26/10/20	01/10/21	25/03/22	11/10/22	18/04/23	30/10/23				
Gas Parameter	Unit	1st	2nd	3rd	4th	5th	6th	Table 1	Table 2	Status
H ₂	Ppm	18	23	20	18	21	19	40	90	Low
CH ₄	Ppm	3	5	4	6	8	8	20	60	Low
C ₂ H ₆	Ppm	9	8	11	10	10	11	15	40	Low
C ₂ H ₄	Ppm	1	1	2	3	3	3	60	125	Low
C ₂ H ₂	Ppm	0	0	0	0	0	0	2	7	Low
CO	Ppm	90	123	124	144	158	168	500	600	Low
CO ₂	Ppm	1902	2154	2072	2200	2336	2282	5500	8000	Low
O ₂	Ppm	10431	10126	9647	9824	9554	9425	-	-	-
N ₂	Ppm	46084	46293	46506	45980	43060	41968	-	-	-
O ₂ /N ₂	-	0.23	0.22	0.21	0.21	0.22	0.22	-	-	-
CO ₂ /CO	-	21.13	17.51	16.71	15.28	14.78	13.58	3-20		Normal
							(CO>1000 ppm) and			
							CO2>10000 ppm			

The results of DGA for all samples that have been tested indicate that there is no disturbance or fault in the transformer based on IEC 60599 and IEEE C 57-104-2008 standards. Monitoring the quality or properties of transformer oil and dissolved gas content can be carried out periodically to obtain well-recorded oil quality and combustible gas concentration data so that we can continue to monitor the condition of the transformer. Transformer oil testing is an important part of routine maintenance to ensure optimal performance of the transformer. This test is carried out to check the physical, chemical, and electrical conditions of transformer insulating oil. The types of testing carried out on transformer oil are physical testing, chemical testing, electrical testing, and screening testing. Physical testing aims to check the visual appearance of the oil, such as clarity, color, and cleanliness (Taha et al., 2021). It also includes measuring the turbidity and viscosity of the oil. Chemical testing is performed to check the insulating qualities of the oil, such as levels of water, acids, and other contaminants. Testing is carried out using methods such as tannin tests, acid tests, and dissolved gas testing (DGA) to detect gases produced by insulation degradation. Electrical testing aims to check transformer insulation and oil dielectric quality. This includes resistivity testing, dielectric power factor, and breakdown voltage testing (Bacha et al., 2012). And filtration testing aims to check the efficiency of the transformer oil filtration system to remove particles and contaminants from the oil.

Analysis of Dissolved Gas in Transformer Oil using Gas Chromatography (GC) is a technique used to monitor and analyze gases dissolved in transformer-insulating oil as shown in Table 1. This process aims to identify and measure the amount of certain gases formed as a result of insulation degradation or other processes in the transformer (Islam et al., 2023). In this analysis, insulating oil samples taken from the transformer were analyzed using the *gas chromatography* (GC) method. GC separates gas mixtures into individual components based on physicochemical properties (Buchacz et al., 2021). Physicochemistry is the characteristics of a substance or compound related to physical and chemical properties. Physicochemistry is various aspects, such as boiling point, melting point, thermal stability, solubility, chemical reactivity, and so on. Delta gas and Rate gas are terms used in DGA in transformer oil. DGA is a technique commonly used to monitor transformer conditions by analyzing gases dissolved in transformer-insulating oil (Gouda et al., 2018). Gas delta is an increase in the concentration of a particular gas in transformer oil between two different points in time. Delta gas indicates a change in condition or potential problem in the transformer. A significant gas delta may indicate an insulation fault or excessive temperature within the transformer.

Table 2. Transformer oil quality testing data

Oil Quality Analysis of Transformer Oils										
Sampling Date			25/10/20	29/09/21	24/03/22	10/10/22	17/04/23	27/10/23	Good	
Received Date			25/10/20	30/09/21	25/03/22	10/10/22	17/04/23	27/10/23		
Test Date			26/10/20	01/10/21	25/03/22	11/10/22	18/04/23	30/10/23		
Gas Parameter	Unit	Method	1st	2nd	3rd	4th	5th	6th	Min Limit	Max Limit
Oil Colour / Appearance	-	ASTM D-1500	1.5 / Light Amber	1.5 / Light Amber	1.5 / Light Amber	1.5 / Light Amber	1.5 / Light Amber	1.5 / Light Amber	-	-
Water Content	mg/ kg	IEC 60814	9	9	9.3	9.2	9.2	9.4	-	30
Acidity	mgKOH/g	IEC 62021-2	0.02	0.02	0.02	0.02	0.02	0.02	-	0.2
Interfacial Tension	mN/m	ASTM D971	38	37.7	37.8	37.6	37.4	37.5	22	-
Oil Quality Index	-	WP 222	1900	1885	1890	1880	1870	1875	160	-
Breakdown Voltage	kV	IEC 60156	74.2	74.5	71.2	72.4	71.1	71.9	40	-
DC Resistivity	G.Ohm/m	IEC 60247	183.5	181.8	175.8	177.9	172.9	168.2	135	-
@90°C DDF	-	IEC 60247	0.0115	0.012	0.012	0.012	0.012	0.012	0.2	-
Viscosity	cSt	ASTM D 445	9.83	9.83	9.83	9.83	9.83	9.82	-	0.5
Kinematic Specific Gravity	-	ASTM D 1298	0.88	0.88	0.88	0.88	0.88	0.88	-	0.91

Transformer oil quality analysis is an evaluation process carried out to assess the condition, reliability, and suitability of the insulating oil used in transformers as shown in Table 2. The purpose of this analysis is to ensure that transformer oil meets the quality standards required to maintain optimal performance of the transformer and extend its service life. Transformer oil quality analysis affects various physical, chemical, and electrical tests. Several parameters that are often evaluated in transformer oil quality analysis are Clarity and Color, Water Level, Acidity, Dissolved Gas Content, Viscosity, and Heat Conductivity. Furan analysis in transformer oil is a method used to measure the amount of furan compounds dissolved in transformer insulating oil. Furan compounds can form because of the thermal degradation process that occurs in transformer insulation. This analysis is important because furan levels in transformer oil can be an important indicator for evaluating the level of insulation degradation and predicting potential transformer failure. The furan analysis process involves sampling transformer oil and extracting furan

compounds from the sample [12]. After that, the furan concentration in the oil is measured using appropriate laboratory analysis techniques at the Muara Karang Block II Generating Unit, such as gas chromatography (GC) or high-performance liquid chromatography (HPLC).

The results of the furan test were correlated with the results of the IFT and acidity tests. The acid attacks the paper insulation producing furans and causing the IFT to decrease. To get better results, analysis of test results is carried out based on trends in test results, not just 1 test result. The thing that needs to be considered in maintaining the condition of the transformer insulation is the oxygen gas content. This gas is very dangerous because it causes oxidation in the transformer. Oxygen in oil comes from leaks and decreased insulation conditions (Emara et al., 2021). An oxygen content of more than 2000 parts per million (ppm) will accelerate the deterioration of the condition of the paper. Oil must be treated if the oxygen content reaches 10,000 ppm. GT 2.1 transformer oil testing using the Dissolved Gas Analysis (DGA) method at PT PLN Nusantara Power has provided results that show the operational condition of the transformer as well as the potential for damage or failure that needs to be watched out for. Based on quantitative analysis, certain gas concentrations in transformer oil have been detected, such as methane (CH₄), ethane (C₂H₆), ethylene (C₂H₄), acetylene (C₂H₂), and hydrogen (H₂). These results provide clues to potential damage within the transformer, with increased concentrations of certain gases indicating problems such as poor lubrication, discharge, or leaks. Additionally, qualitative analysis has identified patterns of dissolved gases in transformer oil, which can provide additional information about the condition of the transformer and possible causes of these gases.

Further discussion of the GT 2.1 transformer oil test results shows that a deep understanding of the gases dissolved in transformer oil is the key to effectively diagnosing transformer conditions. The DGA method has proven to be a very useful tool in monitoring transformer conditions by providing information about potential damage or failure that may occur. These test results also demonstrate the importance of regular sampling and routine analysis to ensure that the transformer is operating in optimal conditions and to identify problems early before they impact transformer performance. In addition, the GT 2.1 transformer oil test results also highlight the important role of environmental and operational factors in influencing DGA analysis results. Variations in temperature, pressure, and transformer operational load can affect gas production and dispersion in transformer oil, so they need to be considered when interpreting analysis results. Therefore, managing these environmental and operational factors is also an important part of an effective transformer maintenance strategy (Noori et al., 2017). Furthermore, the results of the qualitative analysis of gas dissolved in GT 2.1 transformer oil can be used to determine maintenance or repair actions needed to improve the condition of the transformer. For example, identification of leaks or poor lubrication can lead to preventative actions such as repair or replacement of damaged components or oil loss (Ghufron & Prayogi, 2023). Thus, the results of qualitative analysis can provide valuable insights for maintenance teams to take appropriate actions and prevent potential transformer failures.

CONCLUSION

The analysis of GT 2.1 transformer oil testing using the DGA method at PT PLN Nusantara Power reveals the critical importance of this diagnostic tool in maintaining transformer health and operational reliability. Through systematic collection and analysis of oil samples, DGA effectively identified the presence and concentrations of key fault-indicating gases such as hydrogen, methane, ethylene, ethane, and acetylene. Utilizing diagnostic techniques like the Rogers ratio, Duval triangle, and IEC standards, the study accurately diagnosed various fault conditions, including thermal and electrical issues within the transformer. These findings underscore the necessity of regular DGA testing as a component of predictive maintenance strategies. Early detection of potential faults allows for timely interventions, preventing catastrophic transformer failures and unplanned outages, thereby ensuring the continuous and reliable delivery of electrical power. Furthermore, this analysis contributes to extending the operational lifespan of transformers and enhancing the overall efficiency of power systems at PT PLN Nusantara Power. The study highlights the value of integrating advanced diagnostic methods

into routine maintenance practices, affirming DGA's role in safeguarding critical electrical infrastructure. This research provides a robust framework for future transformer maintenance and reliability improvement initiatives.

ACKNOWLEDGEMENTS

The author would like to thank Pertamina University and PT PLN Nusantara Power for the opportunity and support provided in this research. Thank you also to the entire team who contributed to the sampling and analysis of transformer oil.

REFERENCES

- Abdo, A., Liu, H., Zhang, H., Guo, J., & Li, Q. (2021). A new model of faults classification in power transformers based on data optimization method. *Electric Power Systems Research*, 200, 107446. <https://doi.org/10.1016/j.epsr.2021.107446>
- Abu-Siada, A., & Hmood, S. (2015). A new fuzzy logic approach to identify power transformer criticality using dissolved gas-in-oil analysis. *International Journal of Electrical Power & Energy Systems*, 67, 401–408. <https://doi.org/10.1016/j.ijepes.2014.12.017>
- Ali, M. S., Abu Bakar, A. H., Omar, A., Abdul Jaafar, A. S., & Mohamed, S. H. (2023). Conventional methods of dissolved gas analysis using oil-immersed power transformer for fault diagnosis: A review. *Electric Power Systems Research*, 216, 109064. <https://doi.org/10.1016/j.epsr.2022.109064>
- Bacha, K., Souahlia, S., & Gossa, M. (2012). Power transformer fault diagnosis based on dissolved gas analysis by support vector machine. *Electric Power Systems Research*, 83(1), 73–79. <https://doi.org/10.1016/j.epsr.2011.09.012>
- Buchacz, T., Buchacz, J., & Duval, M. (2021). Stray Gassing of Oil in HV Transformers. *IEEE Transactions on Dielectrics and Electrical Insulation*, 28(5), 1729–1734. <https://doi.org/10.1109/TDEI.2021.009520>
- Cheng, L., & Yu, T. (2018). Dissolved Gas Analysis Principle-Based Intelligent Approaches to Fault Diagnosis and Decision Making for Large Oil-Immersed Power Transformers: A Survey. *Energies*, 11(4), Article 4. <https://doi.org/10.3390/en11040913>
- Distributed model predictive control. (2002). *IEEE Control Systems*, 22(1), 44–52. <https://doi.org/10.1109/37.980246>
- Emara, M. M., Peppas, G. D., & Gonos, I. F. (2021). Two Graphical Shapes Based on DGA for Power Transformer Fault Types Discrimination. *IEEE Transactions on Dielectrics and Electrical Insulation*, 28(3), 981–987. <https://doi.org/10.1109/TDEI.2021.009415>
- Faiz, J., & Soleimani, M. (2018). Assessment of computational intelligence and conventional dissolved gas analysis methods for transformer fault diagnosis. *IEEE Transactions on Dielectrics and Electrical Insulation*, 25(5), 1798–1806. <https://doi.org/10.1109/TDEI.2018.007191>
- Ghufron, S., & Prayogi, S. (2023). Cooling System in Machine Operation at Gas Engine Power Plant at PT Multidaya Prima Elektrindo. *Journal of Artificial Intelligence and Digital Business (RIGGS)*, 1(2), Article 2. <https://doi.org/10.31004/riggs.v1i2.21>
- Gouda, O. E., El-Hoshy, S. H., & El-Tamaly, H. H. (2018). Proposed heptagon graph for DGA interpretation of oil transformers. *IET Generation, Transmission & Distribution*, 12(2), 490–498. <https://doi.org/10.1049/iet-gtd.2017.0826>
- Han, X., Huang, S., Zhang, X., Zhu, Y., An, G., & Du, Z. (2023). A transformer condition recognition method based on dissolved gas analysis features selection and multiple models fusion. *Engineering Applications of Artificial Intelligence*, 123, 106518. <https://doi.org/10.1016/j.engappai.2023.106518>
- Islam, N., Khan, R., Das, S. K., Sarker, S. K., Islam, Md. M., Akter, M., & Muyeen, S. M. (2023). Power transformer health condition evaluation: A deep generative model aided intelligent framework. *Electric Power Systems Research*, 218, 109201. <https://doi.org/10.1016/j.epsr.2023.109201>

- Kang, Y., Park, H., Smit, B., & Kim, J. (2023). A multi-modal pre-training transformer for universal transfer learning in metal–organic frameworks. *Nature Machine Intelligence*, 5(3), 309–318. <https://doi.org/10.1038/s42256-023-00628-2>
- Kaur, K., Bhalla, D., & Singh, J. (2022). Hybridized and Complementary Comparative Analysis of Dissolved Gases in a Power Transformer. *IOP Conference Series: Materials Science and Engineering*, 1228(1), 012003. <https://doi.org/10.1088/1757-899X/1228/1/012003>
- Lopes, S. M. de A., Flauzino, R. A., & Altafim, R. A. C. (2021). Incipient fault diagnosis in power transformers by data-driven models with over-sampled dataset. *Electric Power Systems Research*, 201, 107519. <https://doi.org/10.1016/j.epsr.2021.107519>
- Luo, Z., Zhang, Z., Yan, X., Qin, J., Zhu, Z., Wang, H., & Gao, Z. (2020). Dissolved Gas Analysis of Insulating Oil in Electric Power Transformers: A Case Study Using SDAE-LSTM. *Mathematical Problems in Engineering*, 2020, e2420456. <https://doi.org/10.1155/2020/2420456>
- Maccartney, G. R., Rappaport, T. S., Samimi, M. K., & Sun, S. (2015). Millimeter-Wave Omnidirectional Path Loss Data for Small Cell 5G Channel Modeling. *IEEE Access*, 3, 1573–1580. <https://doi.org/10.1109/ACCESS.2015.2465848>
- Marzuki, M., Prayogi, S., & Abdillah, M. (2023, December 29). *Data-Driven Based Model For Predictive Maintenance Applications In Industrial System*. Proceedings of the International Conference on Sustainable Engineering, Infrastructure and Development, ICO-SEID 2022, 23-24 November 2022, Jakarta, Indonesia. <https://eudl.eu/doi/10.4108/eai.23-11-2022.2341596>
- Muhammad, M., Ragadita, B., Prayogi, S., & Saminan, S. (2023). Design of an optical rotation value measurement tool using an arduino device. *Jurnal Pijar Mipa*, 18(5), Article 5. <https://doi.org/10.29303/jpm.v18i5.4811>
- Nanfak, A., Eke, S., Kom, C. H., Mouangue, R., & Fofana, I. (2021). Interpreting dissolved gases in transformer oil: A new method based on the analysis of labelled fault data. *IET Generation, Transmission & Distribution*, 15(21), 3032–3047. <https://doi.org/10.1049/gtd2.12239>
- Ngwenyama, M. K., & Gitau, M. N. (2024). Discernment of transformer oil stray gassing anomalies using machine learning classification techniques. *Scientific Reports*, 14(1), 376. <https://doi.org/10.1038/s41598-023-50833-7>
- Noori, M., Effatnejad, R., & Hajihosseini, P. (2017). Using dissolved gas analysis results to detect and isolate the internal faults of power transformers by applying a fuzzy logic method. *IET Generation, Transmission & Distribution*, 11(10), 2721–2729. <https://doi.org/10.1049/iet-gtd.2017.0028>
- Ramadhan, R. A., Kakke, G. R., Fajar, I. N., & Prayogi, S. (2023). Smart Trash Bin Berbasis Internet Of Things Menggunakan Suplai dari Panel Surya. *G-Tech: Jurnal Teknologi Terapan*, 7(3), 1149–1158. <https://doi.org/10.33379/gtech.v7i3.2777>
- Shanker, T. B., Nagamani, H. N., Antony, D., & Puneekar, G. S. (2017). Case studies on transformer fault diagnosis using dissolved gas analysis. *2017 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 1–3. <https://doi.org/10.1109/APPEEC.2017.8309010>
- Silviana, F., & Prayogi, S. (2023). Utilization of Smartphones in Experiments of Measurement of Electron-Mass Charge Ratio. *International Journal of Engineering and Science Applications*, 10(1), Article 1.
- SuganyaBharathi, M., Iruthayarajan, M. W., Shunmugam, S. S., & Kalaivani, L. (2013). Interpretation of dissolved gas analysis in transformer oil using fuzzy logic system. *2013 International Conference on Power, Energy and Control (ICPEC)*, 245–249. <https://doi.org/10.1109/ICPEC.2013.6527659>
- Taha, I. B. M., Ghoneim, S. S. M., & Zaini, H. G. (2016). A Fuzzy Diagnostic System for Incipient Transformer Faults Based on DGA of the Insulating Transformer Oils. *International Review of Electrical Engineering (IREE)*, 11(3), 305. <https://doi.org/10.15866/iree.v11i3.8453>

- Taha, I. B. M., Ibrahim, S., & Mansour, D.-E. A. (2021). Power Transformer Fault Diagnosis Based on DGA Using a Convolutional Neural Network With Noise in Measurements. *IEEE Access*, 9, 111162–111170. <https://doi.org/10.1109/ACCESS.2021.3102415>
- Taha, I. B. M., Mansour, D. A., Ghoneim, S. S. M., & Elkalashy, N. I. (2017). Conditional probability-based interpretation of dissolved gas analysis for transformer incipient faults. *IET Generation, Transmission & Distribution*, 11(4), 943–951. <https://doi.org/10.1049/iet-gtd.2016.0886>
- Thomas, T. A., Nguyen, H. C., MacCartney, G. R., & Rappaport, T. S. (2014). 3D mmWave Channel Model Proposal. *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, 1–6. <https://doi.org/10.1109/VTCFall.2014.6965800>
- Tra, V., Duong, B.-P., & Kim, J.-M. (2019). Improving diagnostic performance of a power transformer using an adaptive over-sampling method for imbalanced data. *IEEE Transactions on Dielectrics and Electrical Insulation*, 26(4), 1325–1333. <https://doi.org/10.1109/TDEI.2019.008034>
- Wajid, A., Rehman, A. U., Iqbal, S., Pushkarna, M., Hussain, S. M., Kotb, H., Alharbi, M., & Zaitsev, I. (2023). Comparative Performance Study of Dissolved Gas Analysis (DGA) Methods for Identification of Faults in Power Transformer. *International Journal of Energy Research*, 2023, e9960743. <https://doi.org/10.1155/2023/9960743>
- Wang, L., Littler, T., & Liu, X. (2021). Gaussian Process Multi-Class Classification for Transformer Fault Diagnosis Using Dissolved Gas Analysis. *IEEE Transactions on Dielectrics and Electrical Insulation*, 28(5), 1703–1712. <https://doi.org/10.1109/TDEI.2021.009470>
- Wu, X., He, Y., & Duan, J. (2020). A Deep Parallel Diagnostic Method for Transformer Dissolved Gas Analysis. *Applied Sciences*, 10(4), 1329. <https://doi.org/10.3390/app10041329>
- Yang, D., Qin, J., Pang, Y., & Huang, T. (2022). A Novel Double-Stacked Autoencoder for Power Transformers DGA Signals With An Imbalanced Data Structure. *IEEE Transactions on Industrial Electronics*, 69(2), 1977–1987. <https://doi.org/10.1109/TIE.2021.3059543>
- Yang, X., Chen, W., Li, A., Yang, C., Xie, Z., & Dong, H. (2019). BA-PNN-based methods for power transformer fault diagnosis. *Advanced Engineering Informatics*, 39, 178–185. <https://doi.org/10.1016/j.aei.2019.01.001>