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Predictive Maintenance for On Load Tap Changer (OLTC) Failure in Oil Transformer

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Abstract

On-Load Tap Changers are critical components in power transformers, responsible for maintaining stable voltage levels in electrical power systems by adjusting the transformer's turn ratio under varying load conditions. Traditional maintenance strategies for OLTCs are often reactive, leading to delayed fault detection and potential equipment failures, which can result in significant downtime and economic losses. Predictive maintenance strategies, leveraging techniques such as Dissolved Gas Analysis, offer a proactive approach to monitoring the health of OLTCs by detecting early signs of failure through the analysis of fault gases dissolved in the transformer oil. The framework employs DGA, Duval Triangle method and incorporates Failure Mode and Effects Analysis to systematically evaluate potential failure modes, assess their impact on system performance, and prioritize maintenance activities based on quantified risk levels, ultimately enhancing the reliability, safety, and cost-effectiveness of power transformer maintenance programs. By facilitating the proactive identification and resolution of nascent issues within the OLTC mechanism, predictive maintenance methodologies not only curtail the potential for abrupt and severe failures but also contribute to the enhancement of transformer operational efficiency, prolongation of the equipment's functional life, and reduction of disturbances to the power grid, thus bolstering the overall resilience and effectiveness of electrical power network. The predictive maintenance approach ensures more reliable transformer operations by transitioning from reactive to proactive maintenance strategies.

Keywords
On-Load Tap Changer (OLTCs), Predictive Maintenance, Dissolved Gas Analysis (DGA), Failure Mode and Effects Analysis (FMEA) and Duval Triangle Method.

1. Introduction
The On-Load Tap Changer is a critical component of transformers, responsible for maintaining voltage stability under varying loads. The operational status and performance characteristics of the on-load tap changer directly influence the reliability and efficiency of the entire power grid, necessitating careful monitoring and maintenance to prevent unexpected failures and ensure continuous power supply (Zhang et al., 2023). Traditional maintenance strategies often adopt a reactive approach, which can result in delayed fault detection and increased downtime, emphasizing the need for more proactive methodology. Predictive maintenance offers a promising alternative by leveraging advanced diagnostic techniques to facilitate the early detection of potential anomalies and incipient faults, thereby minimizing the risk of catastrophic failures and optimizing maintenance schedules based on the actual condition of the equipment (Behjat et al., 2021). Considering the pivotal role of transformers in upholding grid stability, the implementation of comprehensive condition monitoring strategies becomes not just advantageous, but an indispensable measure for ensuring uninterrupted power supply and preventing potential system-wide disruptions (Gu et al., 2019). Consequently, the rigorous and continuous monitoring of transformer condition emerges as an indispensable practice, ensuring both the accurate assessment of operational performance and the sustained adherence to stringent safety standards, thereby fostering long-term reliability. This study explores the use of Dissolved Gas Analysis for predictive

maintenance, detecting early signs of failure by analyzing fault gases dissolved in transformer oil. This approach aims to transition from reactive to proactive maintenance strategies, ensuring more reliable transformer operations.

2. Methodology

Dissolved Gas Analysis is employed as the primary diagnostic tool to rigorously monitor the health and operational status of On-Load Tap Changers, enabling the proactive detection of potential faults and anomalies through meticulous identification and precise quantification of specific gases dissolved in the transformer oil. By meticulously quantifying the concentrations of key fault gases, including acetylene (C2H2), methane, and ethylene (C2H4), the methodology facilitates a nuanced classification of fault types and a precise assessment of their severity, leveraging established diagnostic techniques such as the widely recognized Duval Triangle method in Figure 1.

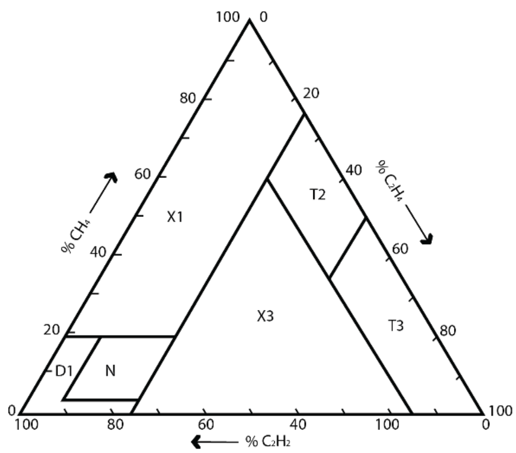

Figure 1. Duval Triangle method for OLTC fault classification based on gas ratios (CH_4, C_2H_4, C_2H_2)

The Duval Triangle method facilitates a sophisticated interpretation of DGA data by mapping the relative concentrations of key fault gases onto a ternary diagram, providing a visual representation that correlates specific gas compositions with distinct fault conditions, thereby enhancing diagnostic accuracy and enabling proactive maintenance decisions. Failure Mode and Effects Analysis is applied to methodically evaluate potential failure modes within OLTCs, focusing on identifying the severity, likelihood, and detectability of each failure mode to prioritize maintenance actions and mitigate risks effectively.

Table 1. Fault zone classification using the Duval Triangle based on gas ratios (CH_4 , C_2H_4 , C_2H_2)

Zone	Identification	Recommended actions
N	Normal operation	
T3	Severe thermal fault T3 (T>700℃) heavycooking	Change the oil, inspect the LTC for coking of contacts
T2	Severe thermal fault T2 (300<T<700℃) cooking	
X3	Fault T3 or T2 in progress (mostly) with light cooking or increased resistance of contacts. Or, severe arcing D2	Test or inspect the LTC for signs of light coking or resistance of contacts, or of severe arcing
D1	Abnormal arcing D1 (outside of zone N)	Inspec the LTC for small sign of arcing
X1	Abnormal arcing D1 or thermal fault in progress	Area still under investigation

The following information is from Table 1, to distinguish between D2 and T3, rinse and change the oil. Afterward, run a few LTC operations (-100), followed by a DGA. If the DGA point remains at the same location as before changing the oil, this may indicate a fault with D2. However, if the DGA point shifts to the left, a fault at T3 is more likely.A structured approach to prioritizing maintenance interventions involves the computation of a Risk Priority Number for each identified failure mode, calculated as the product of the assigned severity score, the estimated frequency of occurrence, and the probability of non-detection, thus enabling a risk-informed decision-making framework for optimizing maintenance resource allocation.

3. Results and Discussion

The application of Dissolved Gas Analysis in conjunction with the Duval Triangle method has demonstrated the capability to accurately identify and quantify fault gases within the transformer oil of On-Load Tap Changers, offering critical insights into the operational health and potential degradation mechanisms affecting these components. Baseline diagnostic assessments, performed prior to any maintenance actions, revealed critically elevated acetylene concentrations, reaching a level of 4075 ppm, in conjunction with a Total Dissolved Combustible Gas concentration of 11,066 ppm; these measurements provided unambiguous evidence indicative of substantial arcing phenomena and significant deterioration of the insulation system integrity within the On-Load Tap Changer (Table 2).

Table 2. Pre- and post-maintenance diagnostic results (gas concentrations).

Gas	Before Filter (ppm)	After Filter (ppm)
Hydrogen (H2)	4645	23
Oxygen (O2)	9363	21227
Methane (CH4)	605	4
Carbon Monoxide (CO)	188	3
Carbon Dioxide (CO2)	1359	9
Ethylene (C2H4)	1385	9
Ethane (C2H6)	168	1
Acetylene (C2H2)	4075	25
Total Dissolved Combustion Gas (TDCG)	11066	65

Post-maintenance evaluations, conducted after targeted interventions, displayed a dramatic reduction in acetylene levels to a mere 25 ppm, accompanied by a commensurate decrease in the Total Dissolved Combustible Gas concentration to 65 ppm; these observations underscored the efficacy of the performed maintenance procedures in mitigating the identified arcing faults and restoring the operational performance of the On-Load Tap Changer towards optimal conditions (Table 3).

Table 3. Duval Triangle fault zone results before and after maintenance

No	Sampling Date	Methane (CH4)	Ethylene (C2H4)	Acetylene (C2H2)	%CH4	%C2H4	%C2H2	Fault Type	Recommended Actions
1	19/3/2015	769	571	1406	28%	21%	51%	X1	Area still under investigation
2	3/9/2016	367	444	2744	10%	12%	77%	N	
3	22/3/2017	1460	3388	5005	15%	34%	51%	X3	Test or inspect the LTC for signs of light coking or resistance of contact, or of severe acring
4	4/5/2018	150	388	449	15%	39%	45%	X3	Test or inspect the LTC for signs of light coking or resistance of contact, or of severe acring
5	23/5/2019	2293	8959	6065	13%	52%	35%	X3	Test or inspect the LTC for signs of light coking or resistance of contact, or of severe acring
6	6/9/2020	244	374	1530	11%	17%	71%	N	
7	26/7/2021	551	1177	3760	10%	21%	69%	N	
8	22/6/2022	1045	3111	4996	11%	34%	55%	X3	Test or inspect the LTC for signs of light coking or resistance of contact, or of severe acring
10	17/2/2024	605	2478	4075	8%	35%	57%	X3	Test or inspect the LTC for signs of light coking or resistance of contact, or of severe acring
11	17/2/2024	4	4	25	12	12%	76%	N	

The following information is from Table 4, to distinguish between D2 and T3, rinse and change the oil. Afterward, run a few LTC operations (-100), followed by a DGA. If the DGA point remains at the same location as before changing the oil, this may indicate a fault with D2. However, if the DGA point shifts to the left, a fault at T3 is more likely. Further confirmatory evidence was obtained through dielectric breakdown voltage measurements, which showed a substantial increase from an initial value of 37 kV to a post-maintenance level of 62 kV; this significant improvement in dielectric strength directly reflects the restoration of the transformer oil's insulating properties and the enhanced ability of the insulation system to withstand high-voltage stresses, thereby contributing to a marked increase in the overall operational safety and long-term reliability of the transformer.

Table 4. Duval Triangle fault zone results before and after maintenance

Sampling Date	Dielectric Breakdown (BDV), kV	Flag
19/3/2015	19	Low
09/03/2016	23	Low
22/03/2017	15	Low
05/04/2018	18	Low
23/05/2019	18	Low
09/06/2020	18	Low
26/07/2021	17	Low
22/06/2022	19	Low
21/06/2023	21	Low
17/02/2024	37	Normal
17/02/2024	62	Normal

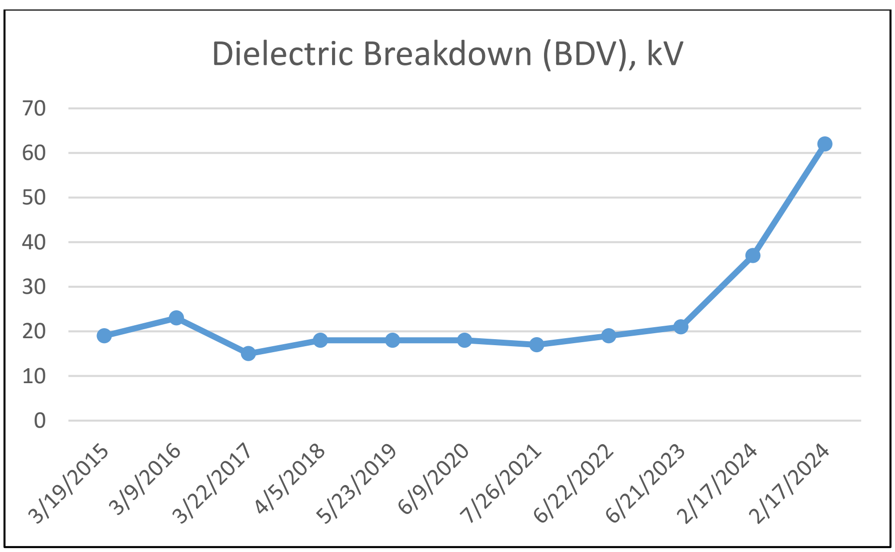

Figure 2. BDV measurements before and after maintenance.

In addition to the aforementioned improvements (Figure 2), post-maintenance moisture content analysis revealed a reduction to 10 ppm, a level that aligns with and adheres to established industry benchmarks and safe operational standards for transformers, signifying the effective removal of moisture and the minimization of its potential detrimental effects on insulation integrity and dielectric performance.

Table 5. Moisture content in oil before and after maintenance.

Sampling Date	Moisture (H2O), ppm	Flag
19/3/2015	66	High
09/03/2016	70	High
22/03/2017	72	High
05/04/2018	80	High
23/05/2019	65	High
09/06/2020	55	High
26/07/2021	56	High
22/06/2022	49	High
21/06/2023	51	High
17/02/2024	43	High
17/02/2024	10	Normal

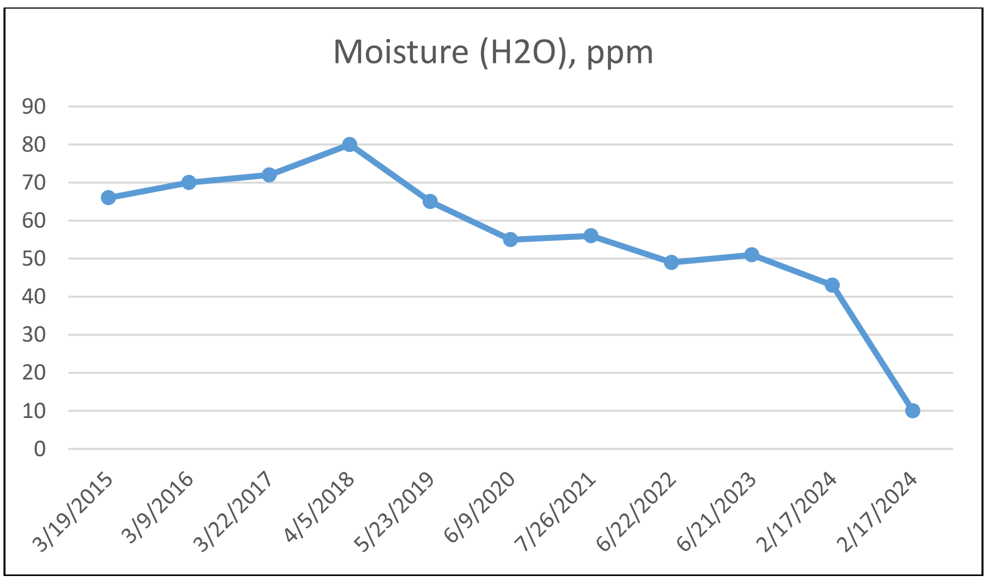

Figure 3. Result Moisute content measurement before and after maintenance.

The synergistic utilization of Dissolved Gas Analysis and complementary diagnostic modalities constitutes a resilient and comprehensive framework (Figure 3), facilitating not only the meticulous evaluation of transformer health but also enabling the implementation of proactive maintenance strategies, which are crucial for mitigating potential risks and bolstering operational dependability.

4. Conclusion

In conclusion, the proactive application of predictive maintenance, incorporating Dissolved Gas Analysis and the Duval Triangle method, significantly improves the detection and mitigation of potential failures in On-Load Tap

Changers; the enhanced fault detection, improved transformer oil condition, and increased operational reliability highlight the value of these advanced diagnostic and maintenance strategies. Future research directions should prioritize the development and validation of advanced hybrid diagnostic methodologies that seamlessly integrate Dissolved Gas Analysis with complementary techniques such as vibration analysis and infrared thermography, enabling a more holistic and nuanced assessment of transformer condition and facilitating the early detection of incipient faults across multiple operational domains. Furthermore, the refinement of diagnostic criteria and threshold values for Dissolved Gas Analysis, tailored to specific transformer designs, operational contexts, and environmental conditions, should be pursued to enhance the sensitivity and accuracy of fault detection, thereby reducing the potential for false alarms and missed diagnoses. The integration of Failure Mode and Effects Analysis into predictive maintenance protocols facilitates the systematic identification and evaluation of potential failure modes within On-Load Tap Changers, enabling the implementation of targeted interventions and risk mitigation strategies, thereby enhancing the overall effectiveness of maintenance efforts and minimizing the likelihood of unexpected equipment failures.

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Biographies

Nurulfatin Fasihah Roslan is a Mechanical Engineering graduate from Universiti Teknologi Malaysia (UTM) with over 5 years of experience in quality control and technical services. She is currently serving as a Technician at TNB Research Sdn. Bhd. (TNB Labs), specializing in Expert Oil Diagnostic Services (EtODS). Her responsibilities include oil filtration, on-site testing of up to 32 parameters in compliance with ISO IEC 17025:2007 standards, calibration of lab equipment, and safe handling and disposal of chemical waste. Prior to joining TNB Labs, she worked in the manufacturing sector at Akashi Kikai Industry (M) Sdn. Bhd., where she played a key role in quality assurance for CVT gearbox production. Her tasks involved implementing quality procedures, performing root cause analysis, and ensuring product compliance with industry standards. Throughout her career, she has completed various technical certifications including AutoCAD 2D/3D, Ansys Workbench, CMM MCOSMOS, and Non-Destructive Testing (PT, MT, UT). Her final year project focused on predictive maintenance for On Load Tap Changer (OLTC) failure in oil transformers, aligning with her strong interest in reliability engineering and system diagnostics. Nurulfatin is passionate about contributing to engineering innovation, particularly in service-based environments that emphasize accuracy, safety, and continuous improvement.

Mohd Faridh Ahmad Zaharuddin is a senior lecturer and a coordinator in the Master of Mechanical Engineering, special track for manufacturing and welding, at the Faculty of Mechanical Engineering, University Teknologi Malaysia, Malaysia. As a director of Authorise Training Body Fakulti Kejuruteraan Mekanikal, his work is focusing in developing new curriculum in university for Education and Qualification of Welding Personnel. His research interests include welding especially in laser weld and friction stir welding, and adaptive manufacturing. He has been appointed as Advisory Board for Welding Institute of Malaysia, and also International Advisory Editor at Journal of Welding and Joining, Korea. With his extensive experience and research, Mohd Faridh Ahmad Zaharuddin significantly contributes to the advancement of knowledge in the fields of welding and the adaptive manufacturing for Education and Qualification of Welding Personnel.