A Comparative Electrical and Physicochemical Parameter Study for Fault Analysis and Health Assessment of Transformers through Insulating Oil

Sujit Kumar Guchhait, Shyam Khatana, Rajendra Kumar Saini*, Anil Kumar Das
Transformer Oil Lab, NTPC Energy Technology Research Alliance, NTPC Ltd., Greater Noida, Uttar Pradesh, India.
*rajendrakumarsaini@ntpc.co.in

Abstract. Power plant transformer health evaluation plays a significant role for efficiency and continuous performance in electric power generation and transmission. When a power transformer is in service, it faces numerous stresses such as electrical stress, thermal stress etc. leading to the release of various C1-C3 hydrocarbon gases (i.e., methane, ethane, acetylene, ethylene, etc.) from the transformer oil and other gases such as CO_2, CO, hydrogen from paper insulation etc. along with various electrical & physicochemical properties such as specific resistivity, Tan Delta, and breakdown voltage (BDV), among others, are altered. In this context, health assessment and continuous monitoring of transformers and failure analysis are crucial to the reliability of a thermal power plant. In this work, we have considered 10 different transformers and comparatively studied these transformers via dissolved gas analysis and various electrical & physicochemical parameters via transformer oil analysis to interpret types of failure and monitor health of a transformer. From this study it has been found that OS6 sample shows the highest amount of hydrogen (2267 PPM) which suggests partial discharge taking place in the transformer. On the other hand, OS2 and OS6 samples show a high amount of acetylene which indicates arcing occurring in the transformer. BDV of OS6 is also less in compared to recommended value. This may be due to the high amount of moisture present in the sample.

Keywords: Power plant transformer, Insulating oil, Aging, Dissolved gas analysis.

1 Introduction

The requirement for the enhancement of electrical power grid infrastructure is of paramount importance, particularly due to the rising distribution of thermal power units to facilitate the current transition to smart grids. Transformers are one of the significant and costly elements of an electricity network, regardless of whether it is utilized for generating, transmitting, or distributing electricity [1]. Any failure in the transformer produces an abrupt disruption in power supply, raises the cost of repair, and affects the efficiency of the power system. As a result, preventing transformer failure and maintaining continuous operation is vital to the entire system's resiliency. The insulation component of an electrical transformer plays a role for its long-term dependability and safety [2]. Cellulose and insulating oil insulation are critical components of oil-immersed transformer insulation design due to their high dielectric strength, which allows them to resist elevated voltages and avoid an arc discharging. It may also monitor the transformer's electrical and chemical conditions and improve heat dissipation in the core and windings that heated up throughout operation due to various power losses [3]. Transformer oil can be categorized into two types: (a) mineral oil and (b) synthetic oil. Mineral oil is also categorized into two parts i.e. naphthenic type mineral oil and paraffinic type mineral oil whereas ester-based and silicone-based oils

S. Shaswattam et al. (eds.), *NTPC Transactions on Energy Research (NTER 2025)*,
https://doi.org/10.2991/978-94-6463-849-3_8

are examples of synthetic oils [4]. A power transformer experiences electrical and thermal stress during operation which leads to various incipient faults. These faults subsequently generate a variety of gases which are partially dissolved in the transformer oil. Thermal breakdown and electrical disruptions are the two main reasons why gas forms within a running transformer. At standard working temperatures, all transformers produce some amount of gas. Transformers oil is a complex chain of hydrocarbon molecules that decompose in thermal or electrical faults. Carbon-carbon and carbon-hydrogen bonds are broken in the primary chemical processes. Hydrocarbon molecules and active atomic hydrogen are formed via this reaction. These components may react with one another to generate the following gases: hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), and ethane (C_2H_6). Moreover, when insulation composed of cellulose is present, thermal breakdown or electric failures produce hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and carbon dioxide (CO_2) [5-6]. Acetylene is mostly associated with arcing, where temperatures can rise to a thousand degrees; ethylene is associated with hot patches ranging from 150 °C to 1000 °C and hydrogen is produced because of partial discharge (PD) [6-8]. Dissolved gas analysis (DGA) is the most important and effective technique for assessing these gases in the condition of oil-filled electrical transformers [6, 8]. Based on the DGA results one can screen the transformer's health condition and implement the suitable preventative maintenance programmed to minimize unforeseen outages. Several ways to analyze transformer failures through DGA have been established, which can be classified into two types: conventional methods and computational methods [8- 12]. However, interpretation of dissolved gases results is often complex and should always be done with care. Roger’s methods, Key gas, Doernenburg Ratios, Duval’s Triangles and Pentagons are the most used in gas-in-oil diagnostics in addition to IEC 60599 [9, 13]. Rogers' approaches comprise three gas ratios: C_2H_2/C_2H_4, C_2H_4/C_2H_6, and CH_4/H_2, which are used for interpreting gases produced in mineral in accordance with IEEE guidelines [14]. The Rogers Ratios gives a lot of information on dissolved gas analysis (DGA) however it suffers from certain drawbacks. Transformer faults are also categorized using the Duval’s Triangle Technique, which is based on the ratios of ethylene, methane and acetylene. It is to be noted that acetylene (C_2H_2) is associated with extremely high temperature/arcing faults, ethylene (C_2H_4) with high temperature faults, and methane (CH_4) with low energy/temperature faults. A diagram illustrating the proportions for each of these gases is positioned on both sides of the triangle. This procedure may be used to find out the six fundamental fault categories. The Duval Triangle approach's fault area limits are depicted in Figure 1 as % CH_4, % C_2H_4 and % C_2H_2. Fault zones are classified as follows in Figure 1: (i) partial discharges (PD) corona type; (ii) D1: discharge of lower energy; (iii) D2: discharge of high energy discharges; (iv) There are three types of thermal faults: T1 (temperature < 300 ºC), T2 (temperature < 300 ºC), and T3 (temperature > 700 ºC). Ahmed Maher et al. explored the dissipation parameters and DGA of minerals oil-based fluids after electrical and thermal failures [15]. Sherif S.M. Ghoneim et al established a new methodology to analyze dissolve as compared with the Duval Triangle, IEC, and Rogers’ methods correspondingly [16]. Joseph J. Kelly has suggested that DGA is an important tool for fault and failure analysis of a transformer and recommended that dissolved-gas analysis may be done on a semi-annual or even a quarterly basis [17].

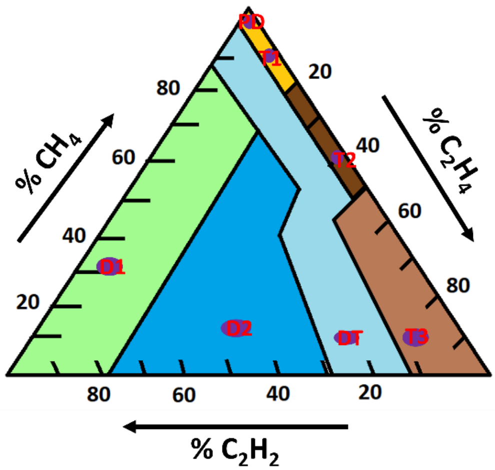

Fig. 1. General Duval Triangle Plot (not in scale) [12]

On the other hand, breakdown voltage (BDV), dissipation factor measurement (Tan δ), moisture analysis, acidity etc are the essential test parameters which can give more insights on the fault analysis [18-20]. The dielectric strength of an insulating material depends on the nature of voltage that is applied, electrode configuration, temperatures, and moisture. By using the outcome of the breakdown strength investigation of transformer oil, appropriate dielectric materials for the associated higher-voltage appliances could be investigated. Based on the previous literature survey, it has been found that there is very few research work are available which deals with failure and health assessment of power plant transformer through insulating oil analysis. This present work will give a broader in-depth concept and interoperation about the transformer oil analysis for failure and heath assessment of a transformer.

2 Experimental

Material and Method: Ten oil samples from different NTPC power plant transformers have been collected. The investigated oils are of mineral type and characterized as received, no further treatment has been done. In this present work oil samples (OS) have been designated as OS1, OS2, OS3, OS4, OS5, OS6, OS7, OS8, OS9 and OS10.

Dissolved gas in the transformer oil has been analyzed through transformer oil gas analyzer (TOGA) which consists of headspace GC of model no 7890B. The test oil samples are carefully transferred into the headspace viz. vial. The gases are removed starting the oil via means of the headspace auto-sampler and injected onto a 8890B GC with two detectors. The head space line temperature is 150 °C. The Thermal Conductivity Detector (TCD) was used for the analysis of hydrogen (H_2), oxygen (O_2), and nitrogen (N_2). The Flame Ionized Detector (FID) with methanizer was used for the analysis of methane (CH_4), carbon mono-oxide (CO), carbon di-oxide (CO_2), ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2). The fraction containing H_2, O_2, and N_2, CH_4, and CO is examined by molecular sieve-5 Å column. H_2, O_2, and N_2 are detected by the TCD. The TCD parameters are as follows: heater temperature is 150°C, reference flow is 25 ml/min and makeup flow gas are 5 ml/min. After passing through the methanizer, CO and methane are detected by the FID. CO_2 and the C-2 product (such as C_2H_4, C_2H_6, etc.) have been separated and extracted from the PLOT-Q column when the molecular sieve column is bypassed. After passing through the methanizer, these are detected by the flame-ionization detector (FID). Argon is employed as a carrier gas to transport the chemicals in the injection loop from the stationary phase to the detectors. The flow rate of argon was 12 ml per minute and has maintained. Argon, air, nitrogen and hydrogen gases are 99.999 % pure. The test method at which 8890B GC-8697A HSS is operating as per ASTM D 3612-C. A brief GC program with ramped temperature is demonstrated in table 1. Moisture content has been measured using coulometric Karl fisher titration method using Mettler Toledo C-30 instrument. The test has been carried out according to ASTM D 6304 to measure water content present in transformer oil.

Breakdown Voltage (BDV) of insulating oil has been determined using Megger™ make an automatic breakdown voltage tester. This approach involves subjecting the oil to a constantly rising alternating voltage until it breaks down. The test has been carried out according to ASTM D877 to measure BDV of insulating transformer oil samples. Tan Delta & resistivity measurement of transformer oil has been carried out by automatic ADTR-2K Plus instrument. To determine the Tan δ, the sample of insulating oil is filled into a test cell. The electrical losses of the cell are then directly compared to those of the low loss standard capacitor after it has been connected to the circuit of an appropriate AC bridge. DC resistivity is determined by measuring the current that flows between the electrodes when a certain voltage is applied to the oil. Dielectric Dissipation Factor (DDF, Tan δ) and specific resistance measurement have been carried out according to ASTM D924 and ASTM D1169 methods respectively.

Total acidity in transformer oil sample has been determined as per ASTM D 974 test method. In this method oil sample is shaken well for uniform distribution of sludge in a glass bottle and agitate until all sediment becomes homogenously suspended in the oil. In a 100 ml plastic cup, introduce a weighed quantity of sample (10-15 gm) & add 60 ml of solvent used for titration (solvent mixture of Toluene: Isopropyl alcohol: water ratio = 500:495:5]. Swirl until the sample entirely gets dissolved in the solvent mixture. Titrate immediately at room temperature till the end point is reached through incremental addition of KOH solution and swirl to disperse the KOH as necessary. The total acidity has been calculated by the subsequent equation (1).

$$\text{Total Acid Number} = \frac{\{(\mathrm{A}-\mathrm{B}) \times \mathrm{N} \times 56.1\}}{W} \text{ mg KOH per gm of oil} \tag{1}$$

Here "A" = amount of KOH (in ml) necessary for the titration, "B" = the KOH (in ml) required for blank test; "N" = normality of KOH solution used, and "W" = weight of the oil sample used. The measurements (water content, tan δ, and resistivity, and breakdown voltage) are carried out at room temperature and ambient pressure.

3 Results and Discussions

Generally, oil has been utilized in transformers for cooling and insulating purposes. Internal condition of a transformer can be diagnosed by carrying out various analyses such as dissolved gas analysis (DGA), moisture analysis, BDV test, Tan delta and acidity test etc. Abnormal electrical or thermal activity can be uncovered by these diagnostic tests.

3.1 Comparative Dissolved Gas Analysis

The most popular diagnostic tool for identifying and assessing transformer defects is DGA analysis. Gases that remain dissolved in the transformer oil can be produced as a result of electrical or thermal transformer faults. When put under potential fault circumstances, the transformer oil and the insulating materials decompose into distinctive byproducts. These suggestive gases, which are produced in the transformer, can be used to identify the failure kind. Hydrocarbons including CH_4, C_2H_2, C_2H_4, and C_2H_6 are also produced as transformer gases, along with H_2, CO, and CO_2. The identification and measurement of these gases can give an early indication of issues emerging with the transformer. This can help with preventive maintenance. and measurement of these gases can offer an early indication of potential issues with electrical equipment. In this present investigation, the detailed DGA analysis has been illustrated in figure 2. From these oil samples, it is found that OS6 gives the highest amount of hydrogen (2267 PPM) which may be due to partial discharge (PD) taking place in the transformer. It is to be noted that according to IEEE guideline, a transformer oil sample should not exceed hydrogen value not more than 100 PPM. On the other hand, OS2 and OS6 show high amount of acetylene which suggests arcing. For fault analysis, there are various methods such as the Dornenburg ratio method, key method, Rogers' ratio method, nomograph method, Duval triangle method, IEC ratio method, and CIGRE method are available. However, in this present study, we will discuss the fault analysis using the most popular Rogers' ratio method and Duval triangle method.

Table 1. GC program parameters

Head Space	Oven Temperature (°C)	70
	Loop Temperature (°C)	150
	Transfer Line Temperature (°C)	150
Oven	Set Value	230
	Rate (°C/min)	24
	Hold time (min)	6
Front Detector (FID)	Heater Temperature (°C)	250
TCD	Heater Temperature (°C)	250

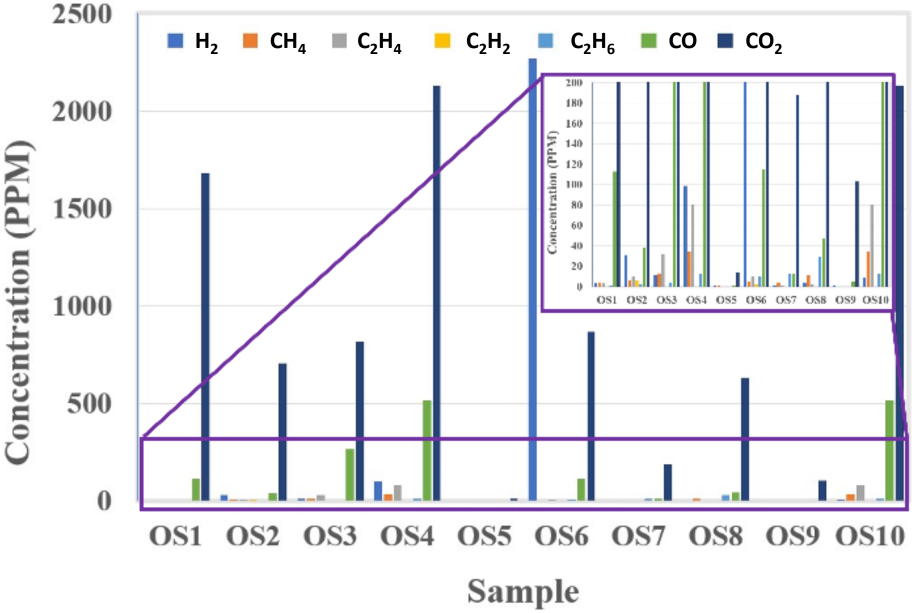

Fig. 2. Dissolved gas concentration in transformer oil samples

3.2 Comparative Fault and Failure analysis through Rogers Method

The most used gas ratio technique for transformer fault investigation is Rogers, which distinguishes numerous thermal fault categories. The gas mixtures ratio of CH_4/H_2, C_2H_4/C_2H_6, and C_2H_2/C_2H_4 are all analyzed using the Rogers technique. Faults are diagnosed using a simple identification technique based on ratio ranges. Employing gas ratios, the Rogers ratio offers a fundamental technique for finding defects. Normal aging, partial discharges regardless of monitoring, and thermal/electrical failure of severity are the situations that can be identified in an oil-insulated transformer.

Table 2 shows the Rogers gas ratio and their fault remarks. From this Rogers ratio table, it can be interpreted that OS5 transformer oil sample does not experience any fault however other transformer oil samples experiences thermal fault (OS1, OS3, OS4, OS10), partial discharge-corona with tracking (OS6) overheating (OS7, OS8) and arcing (OS2). This approach is successful because it links each case's gas examination to the findings of many failure investigations.

3.3 Comparative Fault and Failure analysis through Duval Triangle Method

The Duval Triangle methodology employs the relative position of three different Gases of CH_4, C_2H_4, and C_2H_2 on a triangular diagram together with their values. The triangle is plotted by converting gases through triangular measurements. Partial discharges (PD), low and elevated energy arcing electrical faults and thermal faults (hot areas of varying range of temperatures) are the evident flaws. To diagnose an error, the total amounts of gases (CH_4, C_2H_2 and C_2H_4) are calculated. The fraction of every gas in the whole is then determined by dividing the amount of individual gas by the overall amount. The percentages of the total can be plotted on the triangle to ascertain the diagnosis. Table 3 gives the Duval Triangle Ratio of the dissolved gases and corresponding plot has been depicted in figure 3. From table 3 and figure 3, it can be summarized that OS7, OS8 transformer oil sample experience T1 fault zone, OS1, OS6 transformer oil sample experiences T2 fault zone, OS4, OS10 transformer oil sample experiences T3 fault zone, OS2 transformer oil sample experiences DT fault zone and OS5 transformer oil sample experiences PD fault zone.

Table 2. Rogers Ratios calculation from DGA analysis

Oil Sample	Fault Gas Ratio			Remarks/Fault analysis
	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6	
OS1	0	1.33	3	Thermal < 700 ºC
OS2	0.6	0.19	5	Arcing-high energy discharge
OS3	0	1.18	3	Thermal < 700 ºC
OS4	0	0.38	1	Low temperature thermal fault
OS5	0	1	0	No fault
OS6	0.2	0.02	1	Partial discharge-Corona with tracking
OS7	0	4	0.083	Slight overheating up to 150ºC
OS8	0	2.75	0.068	Overheating to 150 - 200ºC
OS9	0	0	0	Not identified
OS10	0	3.77	6.67	Thermal > 700ºC

Table 3. Duval Triangle Calculation from DGA analysis

Oil Sample	% of CH_4	% of C_2H_4	% of C_2H_2	Fault Zone
OS1	57	42.9	0	T2
OS2	27.3	45.5	27.3	DT
OS3	52	48	0	T2
OS4	29.8	70.2	0	T3
OS5	100	0	0	PD
OS6	80.6	16.1	3.2	T2
OS7	80	20	0	T1
OS8	84.6	15.4	0	T1
OS9	0	0	0	-
OS10	29.8	70.2	0	T3

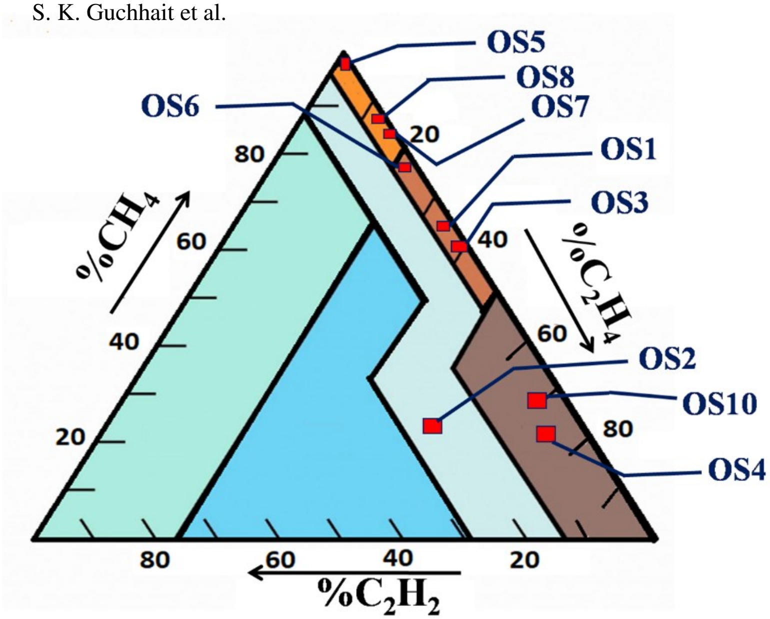

Fig. 3. Duval Triangle Analysis Plot of the Transformer Oil samples

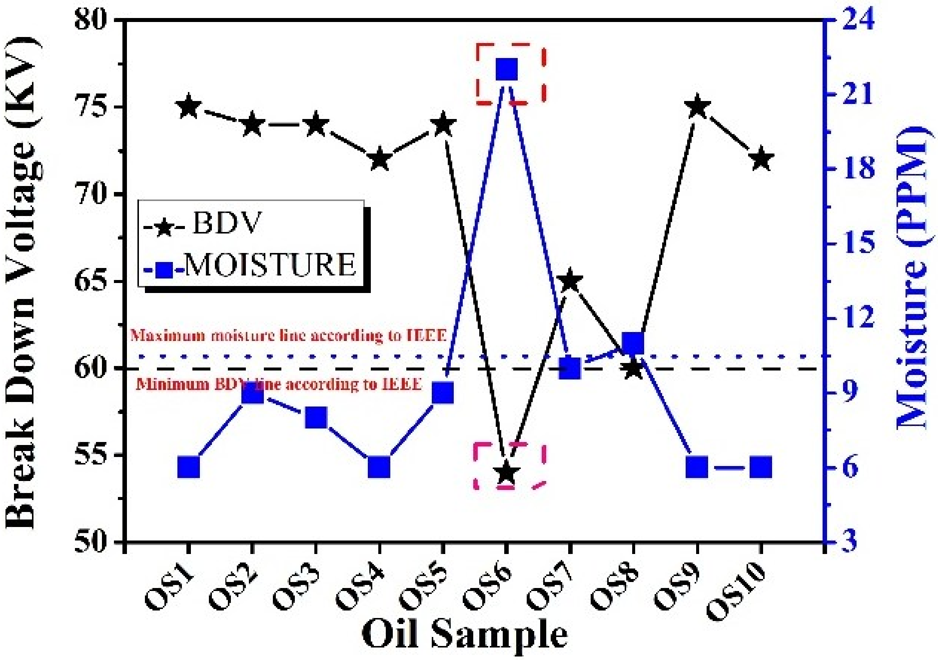

Fig. 4. A comparative relationship between moisture and breakdown voltage

3.4 Moisture and Breakdown Voltage Analysis

Moisture in transformer oil is especially undesirable since it degrades the oil's dielectric characteristics. The amount of moisture in the oil influences the paper protection of a transformer's windings and core. BDV of transformer oil is also known for its dielectric strength. Breakdown voltage is measured by sparking connections among two electrodes drenched in oil and separated by a certain gap. Figure 4 represents a comparative relation between moisture and breakdown voltage of the studied transformer oil samples.

A low BDV value indicates that the oil contains conductive materials and moisture (see figure 4). However, as moisture in transformer oil desorbs, the oil's localized gas concentration increases, which makes bubble formation more likely. The effectiveness of an electrical transformer will be impacted if the insulating oil contains more water than 10 ppm according to IEEE guidelines [21, 22]. In this present investigation, OS6 and OS8 samples show the highest amount of moisture contained in the samples whose BDV value is much less as compared to others (see Table 4).

3.5 Tan delta and Specific Resistivity Analysis

Tan Delta analysis is an important tool for determining the quality of a transformer's insulating system. Tan Delta, commonly referred to as the loss of angle tangent, is a measure of active current to reactive current in insulating substances, which reflects the insulation's dielectric loss [23]. Active Current is the power consumed for heating, also known as the in-phase component, whereas reactive current, known as out-of-phase component. Smaller tan δ values result in lesser dielectric loss and improved insulation effectiveness. Specific resistivity is another significant characteristic of transformer oil. It is measured in ohm-cm at a certain temperature [24]. Oil's resistivity diminishes dramatically as the temperature rises. The inside temperature of e oil will be at ambient temperature immediately after charging a transformer after a long shut down, however the temperature will be quite important and at overload it will reach up to 90°C. As a result, the insulating oil's resistivity should be high at ambient conditions while also being appropriate at high temperatures. There are clear links between Tan-δ and insulating oil resistance. The tan-delta rises while the insulating oil's resistivity decreases, and inversely [25]. From table 4, it has been found that the resistivity and the Tan-δ of different oil samples are different as the oil samples exposed in different conditions as discussed earlier. From table 4, it can be inferred that OS1, OS3, OS4, OS10 transformer oil samples have the smaller Tan delta value with compares to other sample. This indicates that samples have lesser dielectric loss and improved insulation effectiveness. On the other hand, OS1, OS3, OS4, OS10 shows higher specific resistivity value.

3.6 Acidity Analysis

One crucial characteristic of transformer oil is its acidity. The acidity of oil accelerates the oxidation reaction and deteriorates the insulating qualities of paper and coil insulation [26]. It may also lead to sludge formation in the oil in extreme case. The insulating property of oil reduces as the acid value increases [27]. However, in this present study acidity of transformer is within in limit as per standard (see table 4).

Table 4. Various physio-chemical parameters

Oil Sample	BDV (KV)	Moisture Content (PPM)	Tan Delta	Specific Resistivity (GΩ-cm)	Acidity (mg KOH/gm of oil)
OS1	75	6	0.001	32.4	0.05
OS2	74	9	0.003	28.19	0.05
OS3	74	8	0.001	67.35	0.03
OS4	72	6	0.001	61.48	0.05
OS5	74	9	0.01	3.8	0.02
OS6	54	22	0.02	0.48	0.05
OS7	65	10	0.016	2.39	0.05
OS8	60	11	0.019	1.21	0.05
OS9	75	6	0.01	3.9	0.05
OS10	72	6	0.001	61.48	0.05
IEEE recommended Value	60 (Minimum)	10 (Maximum)	0.01 (Maximum)	0.1 (Minimum)	0.3 (Maximum)

4 Conclusion

Analysis of dissolved fault gases and other electrical and other physicochemical parameters such as specific resistivity, Tan-δ, and breakdown voltage (BDV), acidity, moisture, is a feasible and efficient approach for detecting incipient fault and determining their extent. In this study it has been found that OS6 sample shows the highest amount of hydrogen (2267 PPM) which suggests partial discharge (PD) taking place in the transformer. On the other hand, OS2 and OS6 samples show a high amount of acetylene which indicated arcing is occurring in the transformer. It is proven that fault gases in transformer oil deteriorate its electrical insulating properties in huge economic loss. BDV of OS6 is also less in compared to recommended value. This may be due to the high amount of moisture present in the sample. Like this its Tan-δ also reached its maximum value. However, in this present study acidity of all transformers is within the limit as per standard. In accordance with the study, regular inspection of the liquid dielectric medium within the transformer which provides a wealth of information about the oil and overall health of the transformer can help prevent transformer failure.

References

1. Sun, H.C., Huang, Y.C. and Huang, C.M.: A review of dissolved gas analysis in power transformers. Energy Procedia 14,1220-1225 (2012)
2. Arshad, M.I.S.M. and Islam, S.M.: Power transformer critical diagnostics for reliability and life extension. In Canadian Conference on Electrical and Computer Engineering 2004 (IEEE Cat. No. 04CH37513) 625-628. IEEE, Canada (2004)

3. Chandran, L.R., Babu, G.A., Nair, M.G. and Ilango, K.: A review on status monitoring techniques of transformer and a case study on loss of life calculation of distribution transformers. Materials Today: Proceedings 46, 4659-4666 (2021)
4. Wang, X., Tang, C., Huang, B., Hao, J. and Chen, G.: Review of research progress on the electrical properties and modification of mineral insulating oils used in power transformers. Energies 11(3), 487 (2018)
5. Wang, M.V.A.J., Vandermaar, A.J. and Srivastava, K.D.: Review of condition assessment of power transformers in service. IEEE Electrical insulation magazine 18(6), 12-25 (2002)
6. Hamrick, L.: Dissolved gas analysis for transformers. Neta World 01-04 (2009).
7. Singh, S. and Bandyopadhyay, M.N.: Dissolved gas analysis technique for incipient fault diagnosis in power transformers: A bibliographic survey. IEEE Electrical insulation magazine 26(6), 41-46 (2010)
8. Jalbert, J. and Gilbert, R.: Decomposition of transformer oils: a new approach for the determination of dissolved gases. IEEE transactions on power delivery 12(2), 754-760 (1997)
9. Ali, M.S., Omar, A., Jaafar, A.S.A. and Mohamed, S.H.: Conventional methods of dissolved gas analysis using oil-immersed power transformer for fault diagnosis: A review. Electric Power Systems Research 216, 109064 (2023)
10. Mahmoudi, N., Samimi, M.H. and Mohseni, H.: Experiences with transformer diagnosis by DGA: case studies. IET Generation, Transmission & Distribution 13(23), 5431-5439 (2019)
11. Zhang, Y., Tang, Y., Liu, Y. and Liang, Z.: Fault diagnosis of transformer using artificial intelligence: A review. Frontiers in Energy Research 10, 1006474 (2022)
12. Faiz, J. and Soleimani, M.: Dissolved gas analysis evaluation in electric power transformers using conventional methods a review. IEEE Transactions on Dielectrics and Electrical Insulation 24(2), 1239-1248 (2017)
13. Irungu, G.K., Akumu, A.O. and Munda, J.L.: Fault diagnostics in oil filled electrical equipment: Review of duval triangle and possibility of alternatives. In 2016 IEEE Electrical Insulation Conference (EIC), pp. 174-177. IEEE, Canada (2016)
14. Soni, R., Joshi, S., Lakhiani, V. and Jhala, A.: Condition Monitoring of Power Transformer Using Dissolved Gas Analysis of Mineral Oil: A Review. International Journal of Advance Engineering and Research Development 3, 2348-4470 (2015)
15. Maher, A., Mansour, D.E.A., Helal, K. and Abd El Aal, R.A.: Dissolved gas analysis and dissipation factor measurement of mineral oil-based nanofluids under thermal and electrical faults. High Voltage 8(3), 455-465 (2023)
16. Ghoneim, S.S. and Taha, I.B.: A new approach of DGA interpretation technique for transformer fault diagnosis. International Journal of Electrical Power & Energy Systems 81, 265-274 (2016)
17. Kelly, J.J.: Transformer fault diagnosis by dissolved-gas analysis. IEEE Transactions on Industry Applications 6, 777-782 (1980)
18. Rao, U.M., Fofana, I. and Sarathi, R.: Alternative liquid dielectrics for high voltage transformer insulation systems: performance analysis and applications. John Wiley & Sons. New Jersey (2022)
19. Soni, R. and Mehta, B.: A review on transformer condition monitoring with critical investigation of mineral oil and alternate dielectric fluids. Electric Power Systems Research 214, 108954 (2023)
20. Ghani, S.A., Muhamad, N.A., Chairul, I.S. and Jamri, N.: A study of moisture effects on the breakdown voltage and spectral characteristics of mineral and palm oil-based insulation oils. ARPN Journal of Engineering and Applied Sciences 11(8), 5012-5020 (2016)
21. Rao, U.M., Fofana, I. and N'cho, J.S.: On some imperative IEEE standards for usage of natural ester liquids in transformers. IEEE Access 8, 145446-145456 (2020)
22. Nunn, T.: A comparison of liquid-filled and dry-type transformer technologies. In 2000 IEEE-IAS/PCA Cement Industry Technical Conference. Conference Record (Cat. No. 00CH37047), pp. 105-112. IEEE, USA (2000)
23. Chu, D. and Lux, A.: On-line monitoring of power transformers and components: a review of key parameters. In Proceedings: Electrical insulation conference and electrical

manufacturing and coil winding conference (Cat. No. 99CH37035), pp. 669-675 IEEE, USA (1999)
24. Stannett, A.W.: The conductivity of hydrocarbon transformer oil containing water and solid conducting particles. British Journal of Applied Physics 2(4), 110 (1951)
25. Suhaimi, N.S., Ishak, M.T., Rahman, A.R., Muhammad, F., Abidin, M.Z. and Khairi, A.K..: A review on palm oil-based nanofluids as a future resource for green transformer insulation system. IEEE Access 10, 103563-103586 (2022)
26. Tanteh, D.N. and Al-Liddawi, S.Y.: Properties of transformer oil that affect efficiency 48, (2014)
27. Liao, R., Hao, J., Chen, G., Ma, Z. and Yang, L.: A comparative study of physicochemical, dielectric and thermal properties of pressboard insulation impregnated with natural ester and mineral oil. IEEE Transactions on dielectrics and electrical insulation, 18(5), 1626-1637 (2011)