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A COMPREHENSIVE ANALYSIS OF DISSOLVED GASES IN OIL TO MONITOR SUSPICIOUS FAULTS OF DISTRIBUTION TRANSFORMERS IN SOLAR FARM

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Highlights:

- Analysis of DGA data from distribution transformers in solar farm.
- Severity identification of seven gases for fault detection.
- Condition monitoring of distribution transformer health by using seven gases in transformer oil.
- Take action based on condition monitoring.

Abstract: Distribution transformer is a unique asset in a solar farm. While solar panels capture sunlight, the inverter converts it into usable electricity, and the distribution transformer is the key component that enables the seamless delivery of this energy. Fault-free operation of this transformer ensures a proper power supply to the grid. Condition monitoring of transformers is critical for ensuring reliability and extending the operational lifespan at solar farms. Data-driven condition monitoring is one of the most effective approaches for enhancing the operational lifetime of this transformer. This research presents a comprehensive analysis of Dissolved Gas Analysis (DGA) data to predict potential faults in distribution transformers. Utilizing IEEE standards as a validation framework, the Key gas ratio method, Total Dissolved Combustible Gas (TDCG), and Principal gas concentration approaches were employed to identify faults and assess transformers health. The results were analysed using MATLAB software with an M-code algorithm. In this paper, the exceedance level of TDCG (2324 ppm) in transformer 2 is highlighted. Additionally, the CO_2/CO ratios for station transformers 1 to 6 were 7.5, 5.5, 7.6, 7.3, 7.5, and 7.9, respectively. However, in transformer 4, the CH_4/H_2 ratio was also noted to be 0.09. This concentration exceeded the IEEE standard thresholds and was indicative of overheated cellulose and partial discharge faults respectively. The proposed scheme is designed to assist in reducing suspected faults in transformers by enabling timely action based on validated data. This monitoring process can make a significant contribution to reducing the maintenance cost of a solar farm.

Keywords: Distribution Transformer; Dissolved Gas Analysis; Condition Monitoring; TDCG method; Key Gas Ratio Method

1. Introduction

This growing adoption of solar farms as a sustainable energy source necessitates the development of reliable and efficient monitoring systems to ensure optimal operation and performance of critical components. In solar farms, distribution transformers are crucial components to ensure efficient energy transfer to the grid. The typical expected lifespan of a transformer ranges from 20 to 35 years under standard operating conditions. This estimate is primarily influenced by thermal aging of insulation materials, mechanical wear, environmental conditions, and electrical load variations. However, with the implementation of proper maintenance strategies, this lifespan can be significantly extended up to 60 years in many cases (Islam *et al.*, 2023). Reliable and uninterrupted operation is key to lowering energy losses and ensuring system stability. The distribution transformers are subjected to thermal, electrical, and mechanical stresses that can lead to internal faults, deterioration of insulating materials, and overall performance (Ohanu *et al*., 2022; Muthaza *et al*., 2022). The authors (Siswanto *et al*., 2022) studied dissolved gas analysis methods for distribution transformers, specifically using Total Dissolved Combustible Gas (TDCG), Roger Ratio, and Duval Triangle to assess transformer oil quality and detect potential faults.

Faults within transformers often originate from insulation breakdown, overheating, partial discharge, and arcing, which manifest as gases dissolved in the insulating oil (Nadolny *et al*., 2023). DGA has become an indispensable tool for assessing transformer health and monitoring suspected faults. According to (Riedmann *et al*., 2022), the implementation of an online DGA technique for power transformers which is efficient in continuous condition monitoring of transformer insulation systems. This method enables early detection of faults by analysing the concentrations of dissolved gases generated during thermal and electrical faults within transformer oil. The effective monitoring and maintenance of oil relies heavily on the early detection of transformer faults (Ibanga *et al*., 2024; Al-Ameri *et al*., 2022). DGA relies on analysing gases dissolved in the transformer oil, as these gases are by-products of thermal and electrical decomposition of the oil or solid insulation. Gas chromatography (GC) is crucial for DGA because it provides precise, reliable, and detailed insights into the dissolved gases in transformer oil (Deng *et al*., 2017). The GC analysis is a sophisticated technique used to separate, identify, and quantify volatile components in a mixture. In the context of transformer oil analysis, it is used to evaluate dissolved gases produced during transformer operation. The process begins by injecting a small volume of oil or an extracted gas sample into the GC instrument (Fan *et al*., 2019).

Chromatograms also provide consistent learning that makes it easier to find the principal gases from transformer oil (Bakar *et al*., 2014). Identifying common gases such as hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO_2) provides insights into the nature and severity of faults (Mharakurwa *et al*., 2019). The key gas ratio method, as standardized by IEEE C57.104-2008 and 2019, enables fault identification by comparing the ratios of specific gases (IEEE, 2019; IEEE, 2006). For instance, the ratios of CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4, C_2H_2/C_2H_6, and CO_2/CO help to determine whether the fault is thermal, electrical, or involves partial discharge (Mbembati & Bakiri, 2024). This method is widely recognized for its accuracy in categorizing faults such as low-energy discharges, high-energy arcing, and overheating at varying temperature ranges. TDCG analysis is another fundamental approach in transformer condition monitoring. It involves summing up the concentrations of combustible gases to evaluate the overall health of the transformer (IEEE, 2019; IEEE, 2006). According to (Prasojo *et al*., 2020) the TDCG interpretation technique highlights the fault severity and assesses the health index. High TDCG levels often indicate advanced fault stages, prompting immediate maintenance or further investigation. IEEE standards provide threshold limits for TDCG values, which serve as benchmarks to classify the condition of the transformer into normal, cautious, or critical states. The author in papers (Sutikno *et al*., 2021; Suwarno *et al*., 2024) discussed the latest revisions in the IEEE standard for TDCG, emphasizing the importance of dissolved gas evolution rate in assessing transformer operation. By adhering to these standards, maintenance teams can prioritize interventions and reduce the risk of unexpected failures (IEEE, 2006).

In addition to fault detection, principal gas analysis focuses on identifying dominant gases within the oil, which are directly linked to specific fault conditions. For example, the principal gas C_2H_2, along with H_2 which is strongly associated with arcing, H_2 serves as the principal gas, and CH_4 and H_2 are closely linked to partial discharge. C_2H_4 is recognized as the principal gas, and CH_4 is the key indicator of overheated oil, and also as a principal gas of CO together with CO_2 are indicative of overheated cellulose (IEEE, 2006; Lal *et al.*, 2025). Furthermore, CO_2 and other non-combustible gases such as oxygen (O_2) and nitrogen (N_2) are also formed during these fault conditions (Bustamante *et al*., 2019; Abdelwahab *et al*., 2025), and other gas compounds may originate as a little bit when the faults are created. The paper (Nanfak *et al*., 2024; Mahmoudi *et al*., 2019) reviews the analysis of principal gas concentrations alongside key gas ratios and TDCG values to improve diagnostic accuracy. This integrated approach ensures a more comprehensive assessment of the transformer's condition.

This study introduces an integrated diagnostic framework that uniquely combines key gas ratio analysis, TDCG analysis, and principal gas evaluation, all validated against current IEEE standards. Unlike previous studies that have addressed these methods in isolation. This approach specifically targets the challenges of monitoring distribution transformers in solar farm applications. The aim of this research lies in its holistic assessment of transformer health, which not only enhances fault detection accuracy but also offers actionable insights for predictive maintenance. As a result, the expected outcomes include improved operational efficiency, reduced maintenance costs, extended transformer life, and ultimately, a more stable and reliable power distribution system in renewable energy environments.

2. Methods

The proposed data-driven condition monitoring approach of the distribution transformer at the solar farm is designed to assess and analyze transformer health by utilizing dissolved gases. The system comprises six station transformers and the rating is 0.315/33 kV, 1400 kVA for each, and the target electricity generation is 5 MW, which is integrates power from the solar arrays into the AC grid. The six station transformers data were collected to ensure a comprehensive understanding of faults condition. The analysis was employed using the TDCG method, Key gas ratio method, and the Principal gas concentration method, which are widely acceptable techniques for identifying transformer faults. These methods rely on the concentration of gases such as hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO) and carbon dioxide (CO_2). The collected data were analysed using MATLAB, where a custom algorithm was developed using MATLAB's M-code to model and evaluate the transformer condition.

To validate the accuracy and reliability of the results, the measurements were compared against the IEEE standard ranges. This approach ensured precise fault detection and provided actionable insights into the health of the distribution transformers. A visual inspection was conducted to accurately detect four main types of distribution transformer faults, such as arcing, oil overheating, partial discharge, and cellulose overheating.

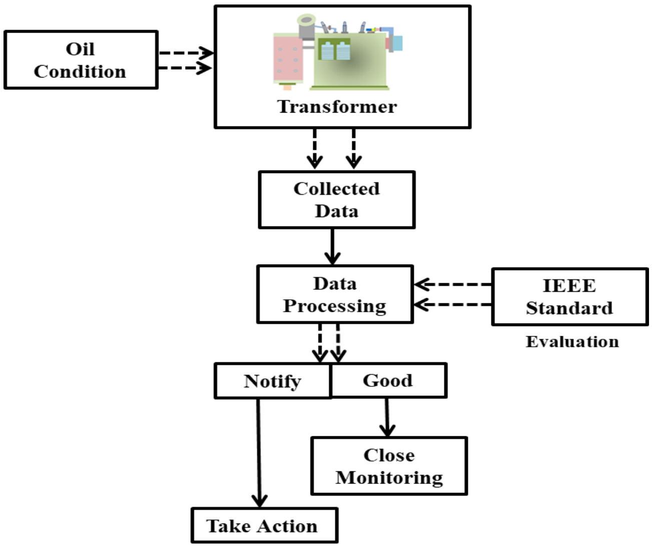

Figure 1. Block diagram of transformer monitoring process

The block diagram in **Figure 1.** Block diagram of transformer monitoring process illustrates a systematic approach to monitoring and managing the condition of a distribution transformer based on its oil condition. The process begins by assessing the oil condition, which is important as the oil serves as an insulating and cooling medium for the transformer. Based on the analysis, decisions are made, if the data indicates normal conditions, the system continues monitoring without immediate action; if anomalies are detected, a notification is generated, which is including in oil test. In cases of abnormal conditions, the transformer undergoes close monitoring to prevent further deterioration. When necessary, corrective actions are taken based on the severity of the issue to ensure the reliability and safety of the transformer. This approach emphasizes timely actions to mitigate potential faults and maintain the operational efficiency of the transformer. **Figure 2** represents a schematic diagram for a fault monitoring scheme in distribution transformers using oil sampling and gas analysis. The process begins with oil sampling from the transformer, followed by the detection of gases dissolved in the oil. The detected gas values are then compared with IEEE standard thresholds to determine the condition of the transformer. If the analysis indicates Case 1, which corresponds to normal gas levels, the system resumes normal surveillance. However, if the results indicate Case 2 or Case 3, which signify abnormal conditions, the focus shifts to analysing principal gases for fault identification. Different gases and their combinations point to specific fault types. C_2H_4 and CH_4 indicate overheated oil, CO and CO_2 indicate overheated cellulose, and H_2 and CH_4 point to partial discharge, and also C_2H_2 and H_2 indicate arcing. This systematic approach enables precise fault identification, facilitating timely corrective actions to maintain transformer health and reliability.

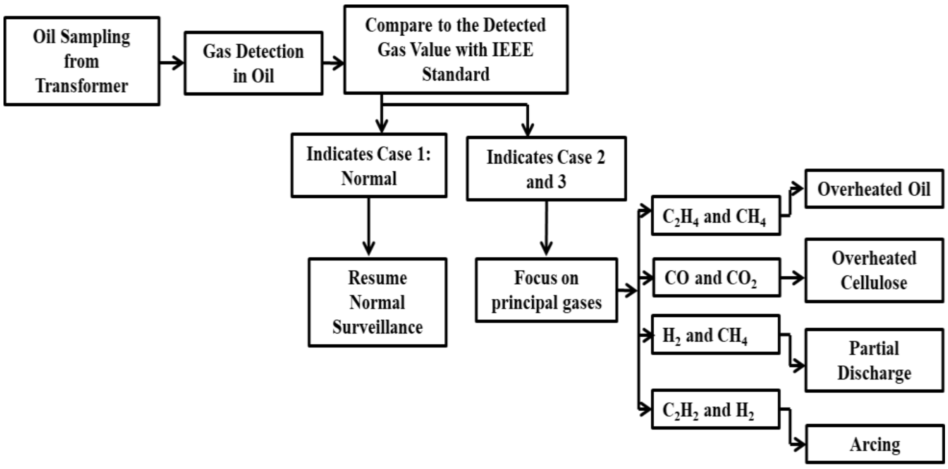

Figure 2. Schematic diagram of fault condition monitoring

The flow chart in **Figure 3** shows a systematic procedure for monitoring the condition of a distribution transformer based on DGA data. The process begins with the input of DGA data. Three primary methods are employed for analysis. In the Key gas ratio analysis, the gas ratio is compared to the threshold values to determine if it exceeds the permissible limit and the limit shown in **Table *4***. Similarly, in principal gas detection, the actual data is checked against the threshold to identify anomalies which are shown in **Table *2***. The threshold in **Table *1***, refers the TDCG analysis, where the total dissolved combustible gas concentration is evaluated to determine if it surpasses the threshold.

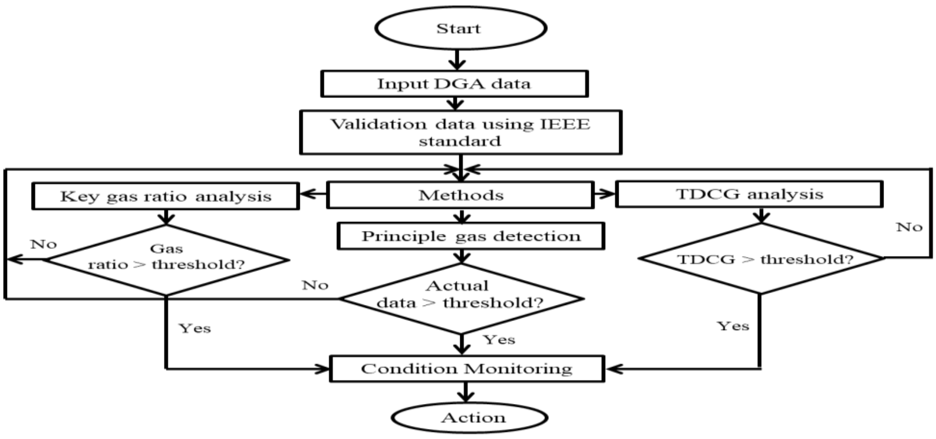

Figure 3. Flow chart for fault condition monitoring

2.1 Total Dissolved Combustible Gases (TDCG)

TDCG represents the sum of the concentration of specific combustible gases dissolved in transformer oil. These gases are typically generated due to insulation degradation or thermal and electrical fault in the transformer. These gases are included in the TDCG calculation. For example, hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), and carbon dioxide (CO2) (IEEE, 2019). Although carbon dioxide (CO_2) is not a combustible gas it is included in the analysis to assess the degradation of paper insulation (Prasojo *et al*., 2020). The concentration of the combustible gases is calculated as follows in equation 1.

$$TDCG = [H_2] + [CH_4] + [C_2H_6] + [C_2H_4] + [C_2H_2] + [CO] \quad (1)$$

Table 1. IEEE standard threshold for TDCG analysis

Case	Status	TDCG gases in (ppm)
1	Normal operation	<720
2	Alert condition	>720-1920
3	Immediate action required	>1920

2.2. Principal Gas Identification

The principal gas identification method in (DGA) refers to the process of determining which specific gases dissolved in transformer oil such as (H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, and CO_2), are most indicative of certain types of faults in a transformer. After the oil sampling, the oil screening is the most effective preliminary assessment to determine the overall condition of the transformer. It involves performing basic tests to evaluate physical, chemical and electrical properties in oil. Then measure the concentration of dissolved gases using specialized equipment such as Gas chromatography or Gel permeation chromatography to identifies higher concentrations of gases (Sutikno *et al*., 2021; Xing *et al*., 2022; IEEE, 2006). If the actual gas input data (obtained from transformer oil testing) exceeds to IEEE threshold ranges, then the model will detect the principal gas level for fault category. **Table *2***, outlines the dissolved gas concentration ranges for various principal gases of transformers, as defined by the IEEE C57.104 standard (Bakar *et al*., 2014; Mharakurwa *et al*., 2019). The limits are expressed in parts per million (ppm) and are used to evaluate the condition of the transformer and detect potential faults.

Table 2. IEEE standard threshold for principal gas identification

Principal Gas	IEEE Limit (ppm)
Hydrogen (H_2)	<100
Methane (CH_4)	<120
Acetylene (C_2H_2)	<1
Ethylene (C_2H_4)	<50
Ethane (C_2H_6)	<65
Carbon monoxide (CO)	<350
Carbon dioxide (CO_2)	<2500

Table *3* presents the dissolved gas concentrations in oil for six station transformers, providing actual data for validation. The gases measured include hydrogen (H_2), methane (CH_4), acetylene C_2H_2, ethylene C_2H_4, ethane C_2H_6, carbon monoxide (CO) and carbon dioxide (CO_2) with values reported in (ppm).

Table 3. Collected data from six distribution transformers at car park solar farm (2024-2025)

Distribution Transformers	Detected Gas in Oil	Gas in (ppm)
	(H_2)	18
	(CH_4)	15
	(C_2H_2)	0
Station Transformer 1	(C_2H_4)	2
	(C_2H_6)	2
	(CO)	1707
	(CO_2)	12756
	(H_2)	38
	(CH_4)	13
	(C_2H_2)	0
Station Transformer 2	(C_2H_4)	2
	(C_2H_6)	2
	(CO)	2269
	(CO_2)	12480

Station Transformer 3	(H_2)	12
	(CH_4)	5
	(C_2H_2)	0
	(C_2H_4)	2
	(C_2H_6)	1
	(CO)	471
	(CO_2)	3587
Station Transformer 4	(H_2)	403
	(CH_4)	36
	(C_2H_2)	0
	(C_2H_4)	1
	(C_2H_6)	4
	(CO)	751
	(CO_2)	5457
Station Transformer 5	(H_2)	21
	(CH_4)	10
	(C_2H_2)	0
	(C_2H_4)	1
	(C_2H_6)	1
	(CO)	862
	(CO_2)	6486
Station Transformer 6	(H_2)	41
	(CH_4)	19
	(C_2H_2)	0
	(C_2H_4)	3
	(C_2H_6)	3
	(CO)	1435
	(CO_2)	11272

2.3. Key Gas Ratio Method

The Key Gas Ratio method is an essential technique for diagnosing faults in distribution transformers using dissolved gas analysis (DGA) (*Jusner et al.*, 2022). According to the IEEE C57.104 standard, recommended limits are provided for gas concentrations and specific gas ratios to facilitate effective monitoring of transformer fault conditions (Nanfak *et al*., 2024; Bustamante *et al*., 2019).

Table 4. IEEE standard threshold for key gas ratio analysis

Fault type	CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_4/C_2H_6	CO_2/CO	Typical fault
Partial Discharge (PD)	<0.1	<0.01	-	-	-	Partial discharge (PD) in oil
Thermal fault (T1)	0.1-1	<0.1	<0.1	<1	>3	Low temperature overheating
Thermal fault (T2)	0.1-1	<0.1	<0.1	1-3	>3	Medium temperature overheating
Thermal fault (T3)	>1	<0.1	<0.1	>3	>3	High temperature overheating
Discharge in low Energy (D1)	>0.1	0.1-3	0.1-1	-	-	Low energy arcing
Discharge in high Energy (D2)	>1	>3	>1	-	-	High energy arcing

The interpretation of the fault conditions is based on the analysis of various key gas ratios, as outlined in **Table *4***. **Table *4*** represents IEEE key gas ratio limit for analysing actual gas ratios to detect particular faults, categorize their types and determine potential causes in a distribution transformer.

3. Results and Discussion

TDCG values ranging between (>720-1920) ppm correspond to case condition 2 in **Table *1*** which requires for increased monitoring and diagnostics. Based on condition monitoring, in station transformer 1, 4, 5, and 6, the TDCG levels of 1744 ppm, 1195 ppm, 895 ppm and 1501 ppm, respectively are both within case condition 2 in **Table *1***. These monitoring results are an alert condition for the transformer and requires close attention to prevent further deterioration. In this condition the action should need to take such as, increase monitoring and identify gas composition, historical DGA data evaluation with inspection and diagnosis. Again, with a TDCG value of 491 ppm in station transformer 3, which falls below the standard threshold for case condition 1 in **Table *1*** (<720 ppm). The transformer is considered to be in a normal operating condition with no immediate concerns. At this level, the recommended actions are routine monitoring and maintenance as part of the standard operational practices. Periodic dissolved gas analysis (DGA) should be conducted to track gas levels and monitor any early signs of fault. But in transformer 2, the TDCG value is 2324 ppm. This station transformer exceeded the threshold for case condition 2 (>1920 ppm), and falls into case condition 3 in **Table *1***, which indicates a potentially serious issue that requires immediate attention. This condition indicates that the transformer may be experiencing significant internal problems, such as overheating, arcing, or partial discharge. It is a highly alarming condition and need to address promptly to prevent catastrophic failure. The recommended actions include reducing the transformer load if possible to limit further stress and immediately conducting a detailed dissolved gas analysis (DGA) to identify the specific gases contributing to the elevated TDCG value. A comprehensive inspection of the transformer's cooling system, insulation, and other critical components should be performed to locate and assess the fault. If the rate of gas generation is accelerating, taking the transformer offline for a more thorough investigation and repair may be necessary.

Based on the **Figure *4*** to **Figure 9**, the condition of the station transformers 1, 2, 3, 5, and 6 can be evaluated by identifying fault types associated with specific gas concentration. In this case, the levels of H_2 and CH_4, C_2H_2 and H_2, C_2H_4 and CH_4 are within their respective threshold limits, indicating no significant evidence of partial discharge, arcing and overheated oil faults respectively. However, carbon monoxide (CO) and carbon dioxide (CO_2) have exceeded their threshold limits, indicating the degradation of cellulose insulation due to overheating. The presence of elevated CO and CO_2 specifically indicates thermal decomposition of paper or insulation materials, commonly associated with a thermal fault. The extent of the increase in CO and CO_2 beyond the standard threshold is marked in khaki colour, in station transformer 1, 2, 3, 4, 5 and 6, including **Figure *4***b, **Figure *5***b, **Figure *6***b, **Figure *7***b, **Figure *8***b and **Figure 9**b are simultaneously active overheated cellulose to highlight the severity of the condition and likelihood of advanced cellulose degradation. In station transformer 4, H_2 is also exceeded the threshold limit which is indicates the partial discharge, and shown in **Figure** ***7***a, marked as yellow colour threshold, and khaki colour indicates the active partial discharge.

3.1. Station Transformer 1

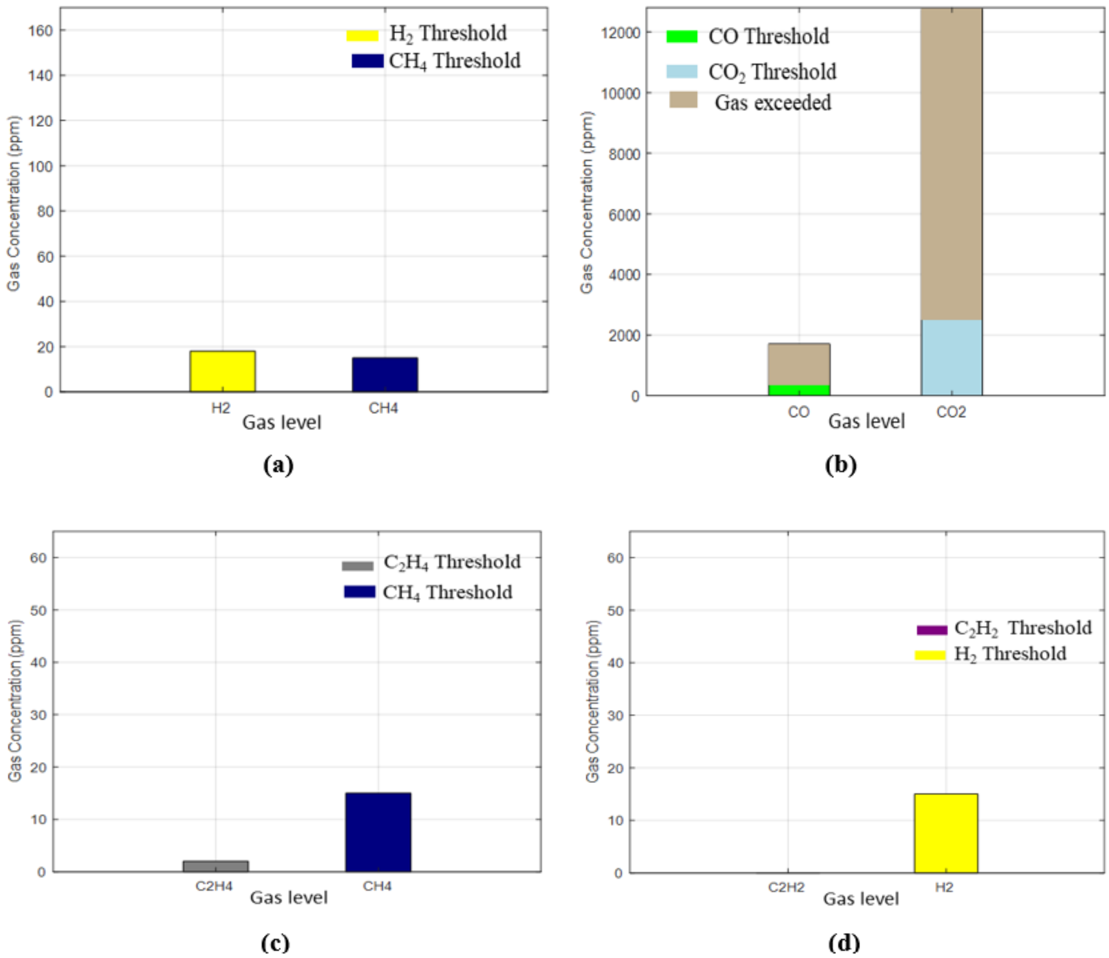

Figure 4. (a) Inactive partial discharge; (b) Active overheated cellulose; (c) Inactive overheated oil; (d) Inactive arcing

3.2. Station Transformer 2

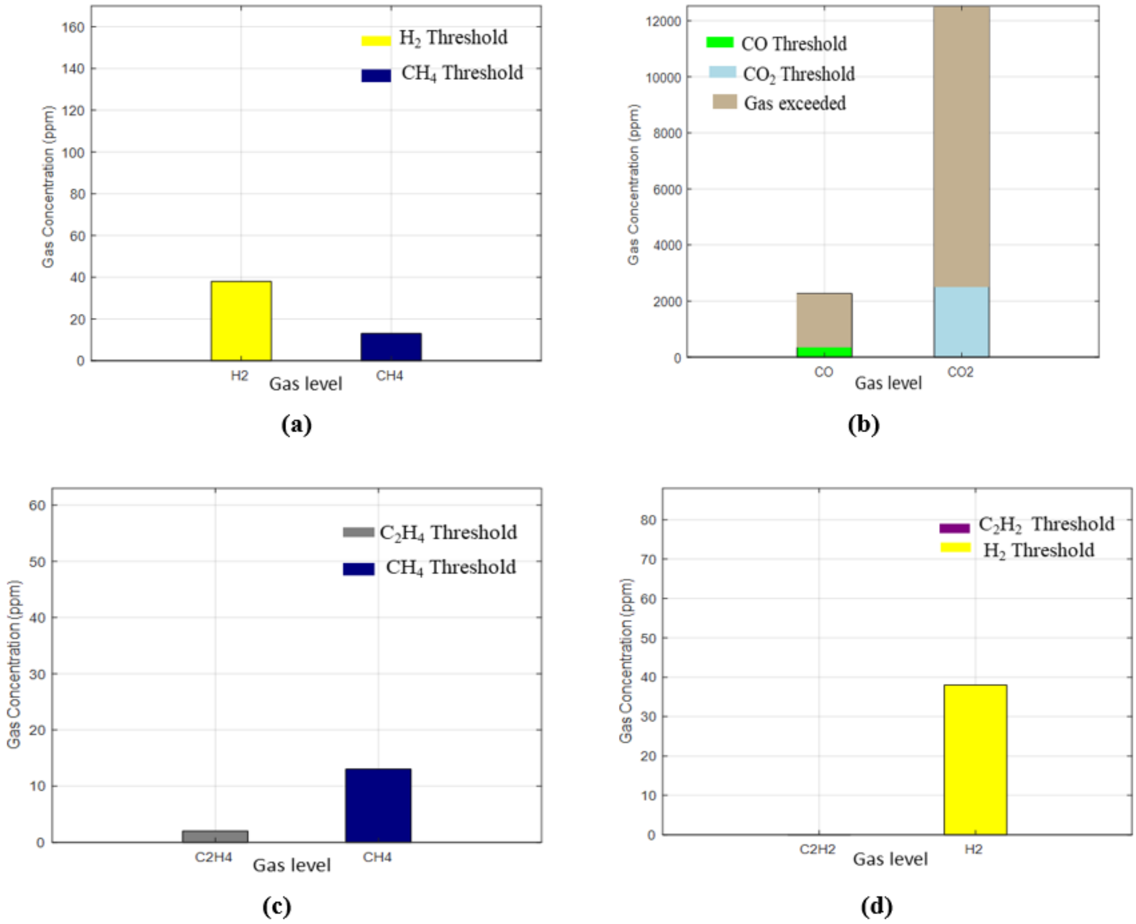

Figure 5. (a) Inactive partial discharge; (b) Active overheated cellulose; (c) Inactive overheated oil; (d) Inactive arcing

3.3. Station Transformer 3

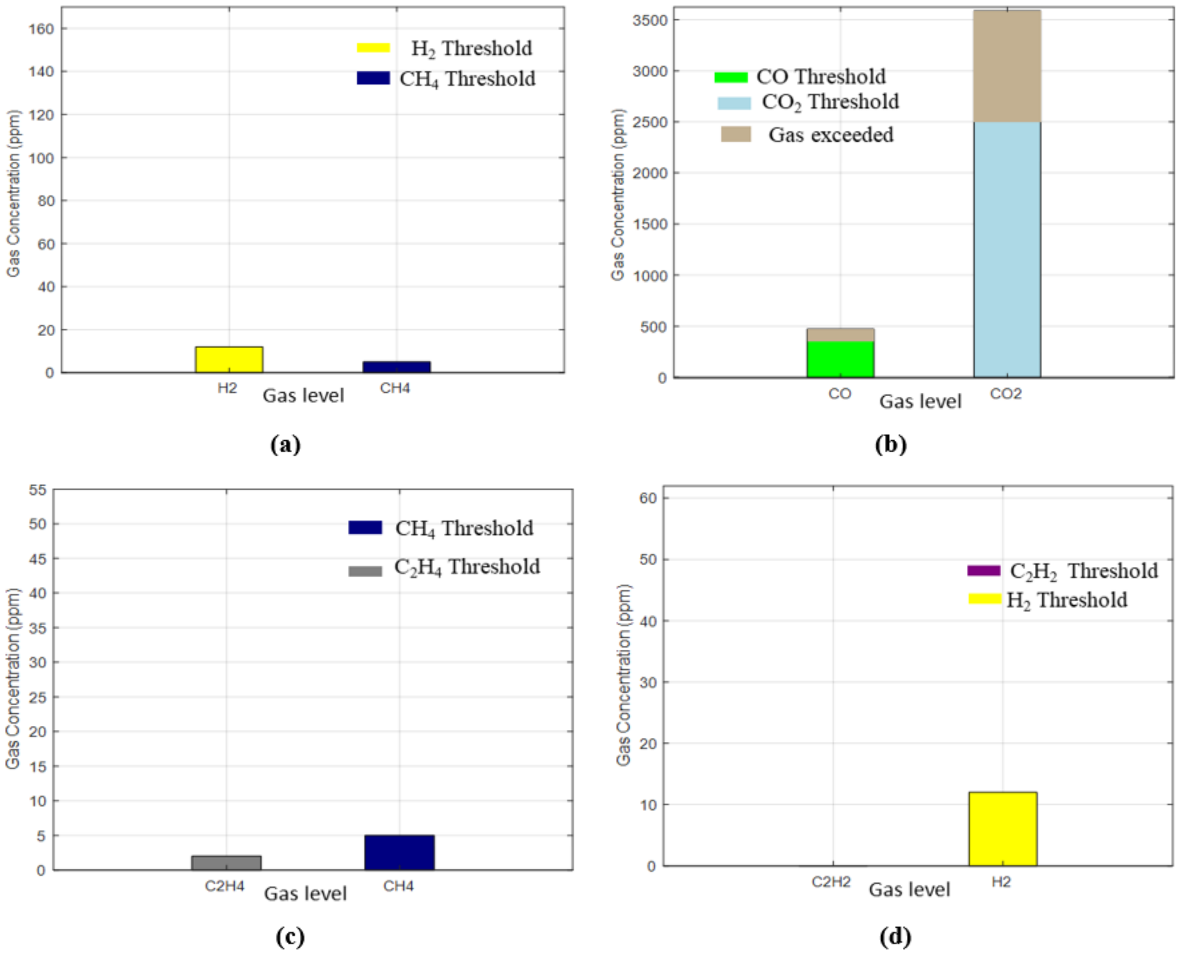

Figure 6. (a) Inactive partial discharge; (b) Active overheated cellulose; (c) Inactive overheated oil; (d) Inactive arcing

3.4. Station Transformer 4

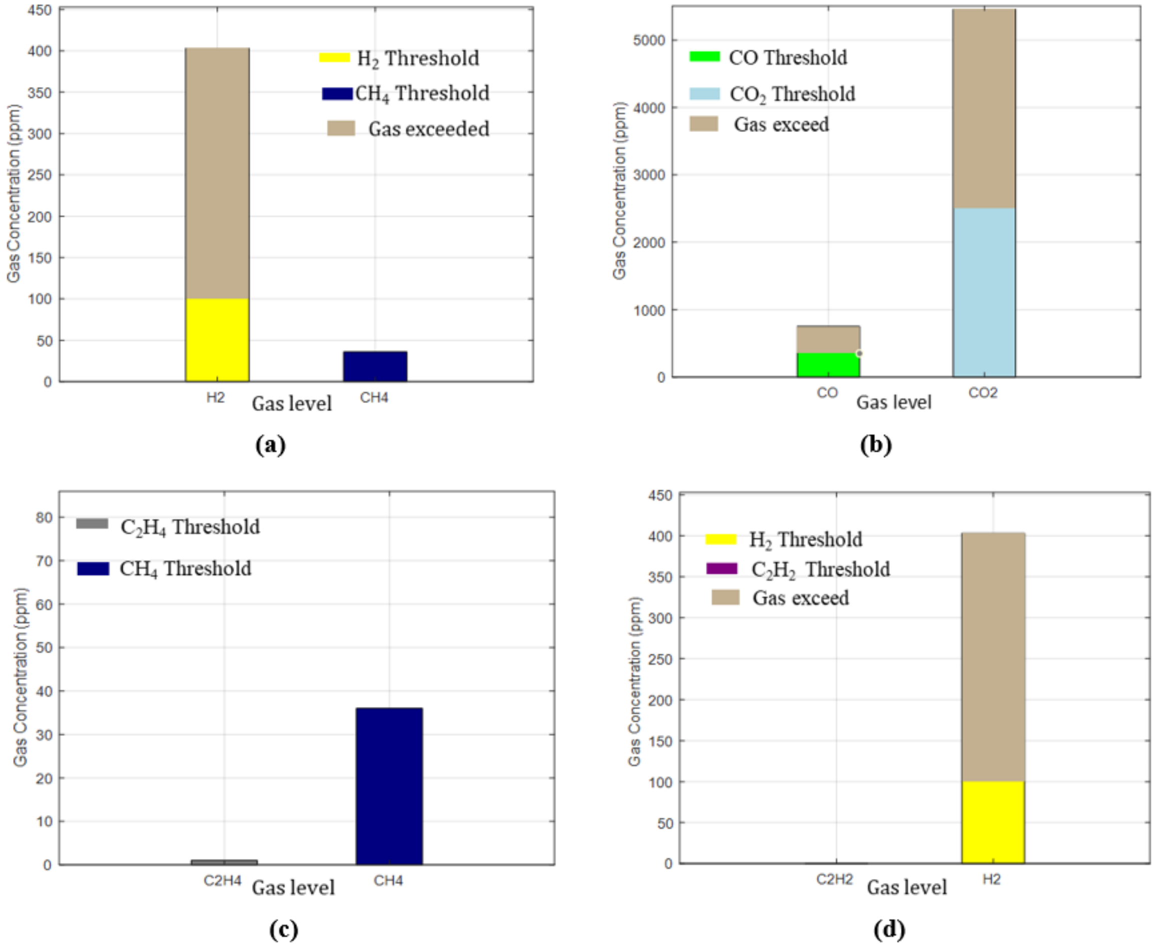

Figure 7. (a) Active partial discharge; (b) Active overheated cellulose; (c) Inactive overheated oil; (d) Inactive arcing

3.5. Station Transformer 5

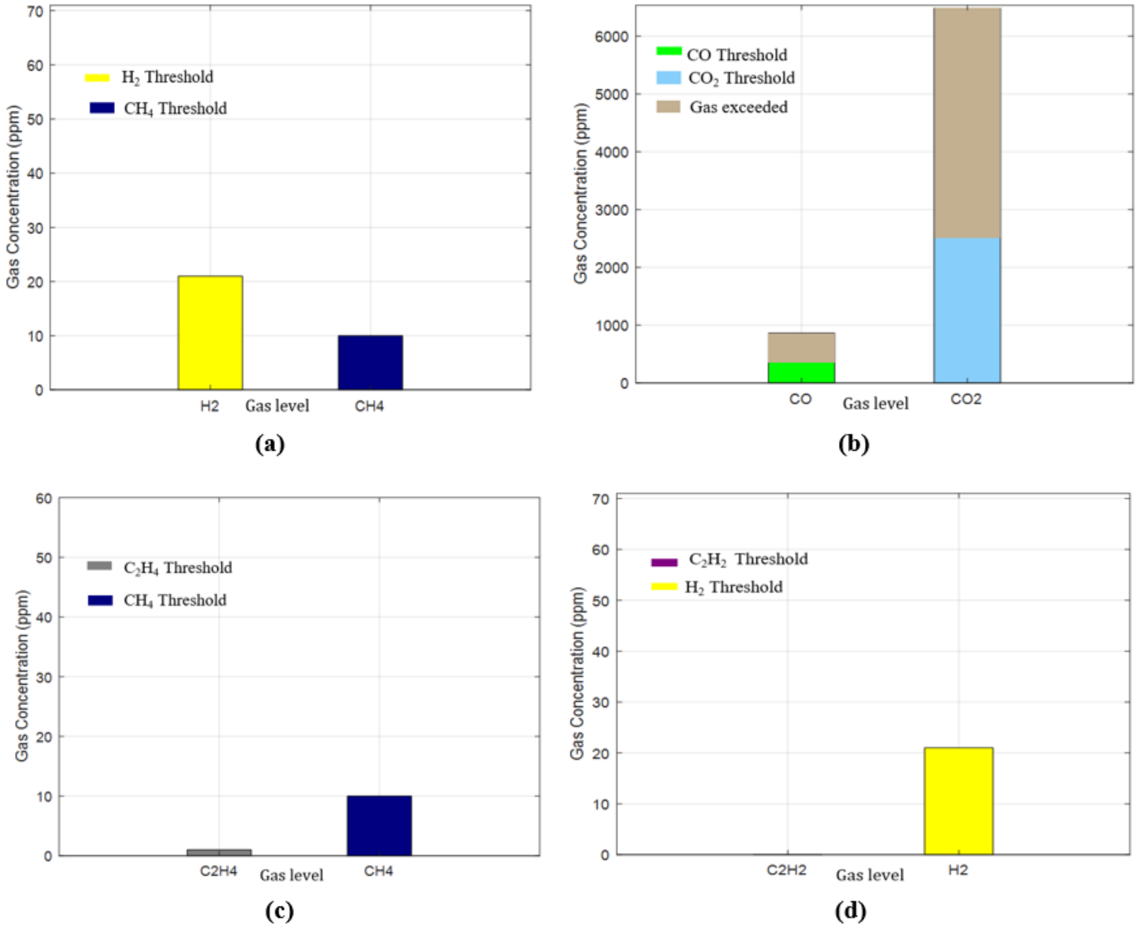

Figure 8. (a) Inactive partial discharge; (b) Active overheated cellulose; (c) Inactive overheated oil; (d) Inactive arcing

3.6. Station Transformer 6

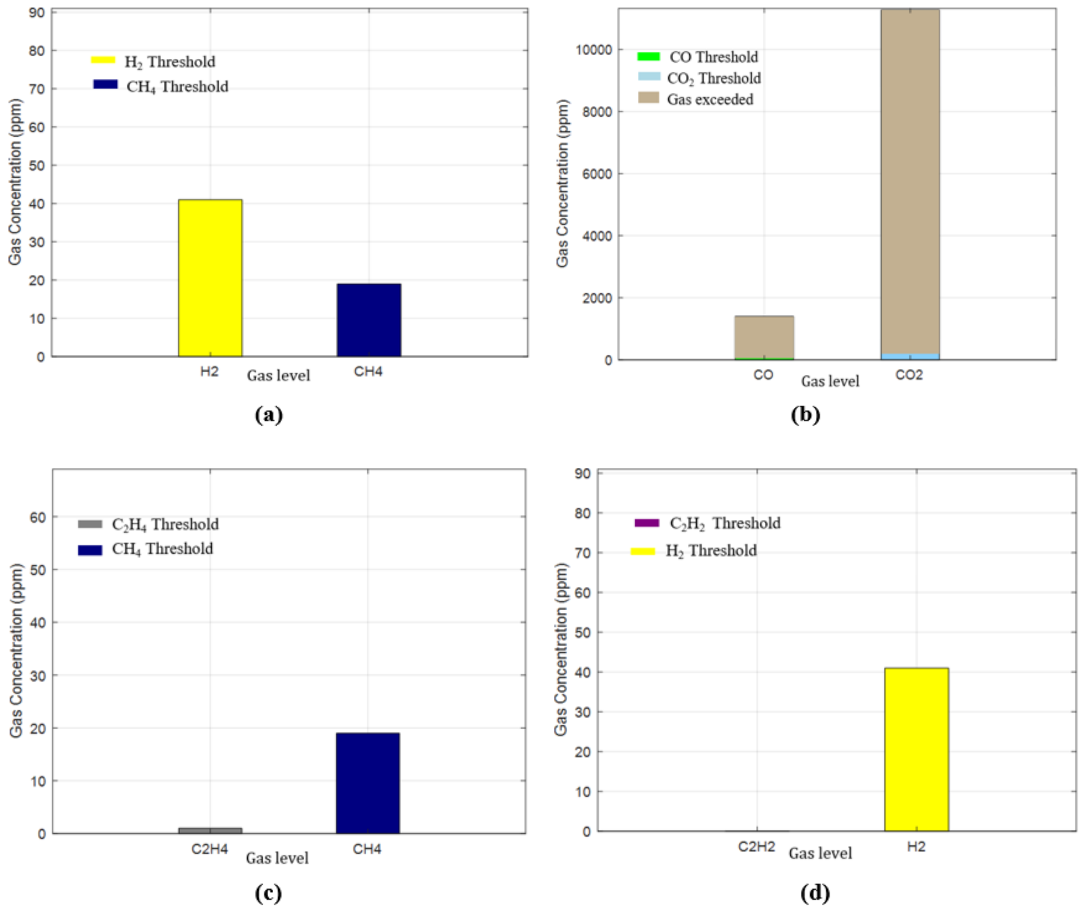

Figure 9. (a) Inactive partial discharge; (b) Active overheated cellulose; (c) Inactive overheated oil; (d) Inactive arcing

The diagnostic and analysis of six station transformers using key gas ratio methods reveals varied fault condition, which are discussed below in **Table *5***. The results expressed based on **Table *4***.

Table 5. Key gas ratio analysis

Distribution Transformer	Key Gas Ratios				
	CH_4/H_2	C_2H_2/C_2H_4	C_2H_2/CH_4	C_2H_4/C_2H_6	CO_2/CO
Station Transformer 1	0.8	0	0	1	7.5
Station Transformer 2	0.3	0	0	1	5.5
Station Transformer 3	0.4	0	0	2	7.6
Station Transformer 4	0.09	0	0	0.3	7.3
Station Transformer 5	0.5	0	0	1	7.5
Station Transformer 6	0.5	0	0	1	7.9

Station transformer 1 exhibits a CH_4/H_2 ratio of 0.8, indicating inactive partial discharge. The C_2H_4/C_2H_6 ratio was 1, the CO_2/CO ratio of 7.5 indicated thermal fault T2, high temperature cellulose degradation, and the acetylene ratio C_2H_2/CH_4 was 0 that means inactive arcing fault. In station transformer 2, the CH_4/H_2 ratio of 0.3, the C_2H_4/C_2H_6 ratio was 1, and C_2H_2/CH_4 ratio was 0. There is no active faults, but the CO_2/CO ratio was 5.5, which indicate thermal fault T2, high temperature cellulose degradation. In station transformer 3, the CH_4/H_2 ratio of 0.4, C_2H_4/C_2H_6 was 2, and C_2H_2/CH_4 was 0, indicating inactive faults but CO_2/CO was 7.6, which is indicated overheating fault. In station transformer 4, the CH_4/H_2 ratio of 0.09 indicates active partial discharge. The ratio of CO_2/CO is 7.3, also detected thermal fault with high temperature cellulose degradation. The ratio of C_2H_4/C_2H_6 was 0.3 and the ratio of C_2H_2/CH_4 was 0, indicating inactive faults. Also, in station transformer 5 and 6, the CO_2/CO ratios were 7.5 and 7.9 are indicating thermal fault, and the other ratios were inactive for creating a fault. These evaluated outcomes are express in **Figure *10*** for understanding the gas ratio of each station transformer in a 5 MW solar farm.

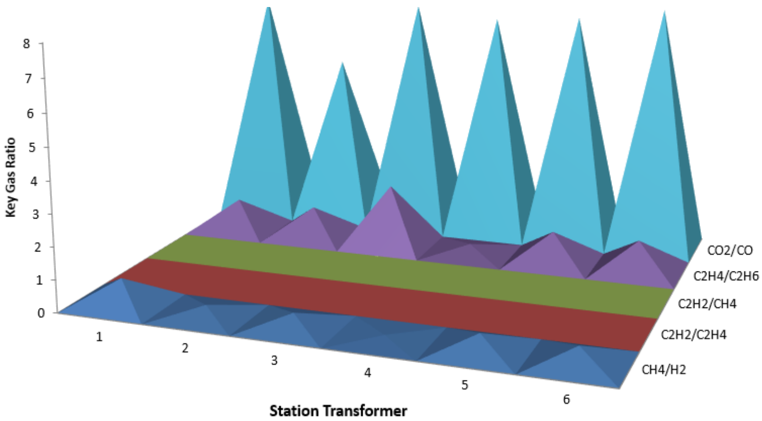

Figure 10. Gas ratio analysis of six station transformers

Figure *10* represents the key gas ratios used in Dissolved Gas Analysis (DGA) for monitoring transformer oil condition. The CO_2/CO ratio is significantly higher than the other ratios, indicating overheating of cellulose within the transformers.

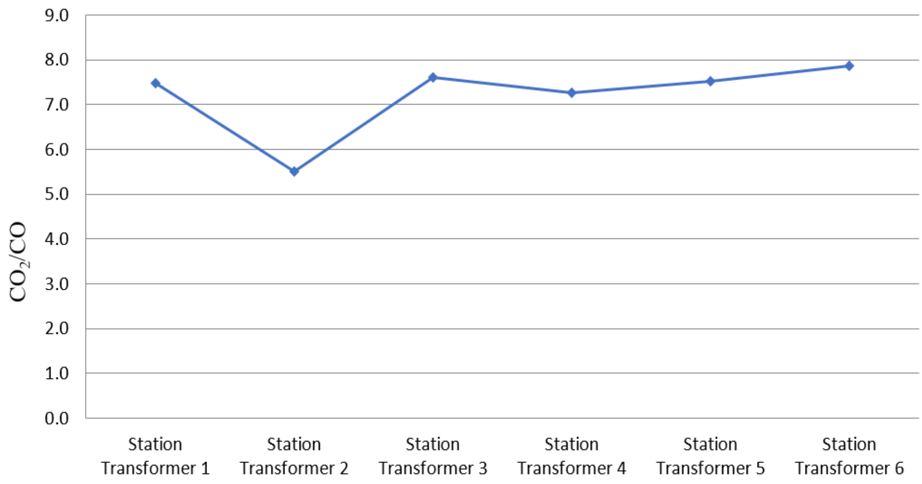

Figure 11. CO and CO_2 ratio analysis

On the other hand, the CH_4/H_2 ratio is moderate, which indicates active partial discharge in station transformer 4. Partial discharge is a low-energy electrical fault that generates small quantities of H_2 and CH_4 gases. The C_2H_2/C_2H_4, C_2H_2/CH_4, and C_2H_4/C_2H_6 ratios are low or negligible, indicating there are no significant faults. Overall, the results highlight overheating of cellulose as the primary concern, with minor partial discharge activity, and no evidence of severe overheating oil and arcing. **Figure *11*** represents the CO/CO_2 ratio for six station transformers, which is a key indicator in transformer oil analysis for condition monitoring. The ratio provides insight into the degradation of insulation materials and potential thermal faults within the transformer. From the plotted data, it is evident that the CO/CO_2 ratio fluctuates across different transformers. The station transformer 4 indicates the lowest ratio, suggesting that it experiences relatively lower insulation degradation.

In contrast, the first transformer starts at a higher ratio, followed by a decline at the second transformer and then a significant increase at the third transformer. This pattern may indicate varying levels of insulation aging or operational condition among the transformers. The gradual increase from the fourth to the sixth transformer indicates a steady rise in insulation deterioration, potentially due to prolonged operation or elevated temperatures. Transformers with consistently high CO/CO_2 ratios may require further investigation for overheating, insulation failure, or mechanical stress. **Table *6*** illustrate the fault severity from key gas ratio and recommends action for distribution transformer protection at a solar farm. The results emphasize the importance of continuous monitoring and maintenance strategies to prevent potential failures and extend the lifespan of the transformers in solar farm.

Table 6. Faults severity and action

Transformer	Monitored Condition	Gas Exceed	Recommended Action
Station Transformer 1	High	CO and CO_2	Take immediate caution and proceed with resampling without delay. Perform a DGA and Furan analysis promptly. Evaluate the need for removing the transformer from the service and consult the manufacturer for expert recommendation.
Station Transformer 2	High	CO and CO_2	Exercise extreme caution. Resampling at immediate basis. DGA and furan analysis to be carried out. Consider removal from service and advice manufacturer. Increase sampling frequency.
Station Transformer 3	Normal	CO and CO_2	Exercise caution and determine load dependence. Increase sampling frequency. Resampling at 3-monthly basis. DGA and furan analysis to be carried out.
Station Transformer 4	High	CO, CO_2 and H_2	High concentration of H_2, CO and CO_2 gases. Exercise extreme caution. Increase sampling frequency. Plan outage and advice manufacturer.
Station Transformer 5	High	CO and CO_2	Continue monitor the dissolved gases.
Station Transformer 6	High	CO and CO_2	Increase sampling frequency of TDCG, regular monitor of oil quality.

4. Conclusion

Effective condition monitoring of distribution transformer oil is essential to ensure the reliable operation of transformers at solar farm, securing uninterrupted power supply to consumers. This paper demonstrated a robust data driven approach to monitor distribution transformer health by analysing dissolved gases data. By exploiting Key gas ratio methods, the Total Dissolved Combustible Gas (TDCG) method, and Principal gas concentration techniques, potential faults were identified and evaluated for their impact on transformer reliability. The analysis revealed critical insights into transformer health across six station transformers at a 5 MW solar farm. Notably, transformer 2 exhibited an alarming TDCG level of 2324 ppm, significantly exceeding the IEEE standard threshold, indicating a potential fault condition. Additionally, our condition monitoring scheme indicate high concentration of CO and its

CO_2/CO ratios, those are exceeding acceptable limits and detect overheating of cellulose insulation. Furthermore, transformer 4 exhibited a high concentration of H_2 and its CH_4/H_2 ratio of 0.09, surpassing IEEE-defined thresholds, which points to the occurrence of partial discharge, which is a precursor to electrical failure. These findings emphasize the critical need for timely intervention based on data-driven diagnostics. The proposed monitoring framework highlights how exceeding standard thresholds can predict specific fault mechanisms like overheated cellulose, overheated oil, arcing, and partial discharge. By implementing corrective actions informed by this analysis, utilities can effectively mitigate potential transformers failures, thus enhancing reliability and extending operational longevity. This monitoring scheme may help with future sustainable energy production in a solar farm.

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Credit Author Statement

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Conflicts of Interest

There is no conflict of interest.

Artificial Intelligence (AI) Transparency Statement

The authors acknowledge the use of ChatGPT (OpenAI) as an assistive tool during the preparation of this manuscript. The AI tool was used to support language editing, sentence restructuring, and improvement of clarity and readability of the text. The AI did not contribute to the research design, data collection, data analysis, interpretation of results, or decision-making. All scientific content, results, interpretations, and conclusions are solely the responsibility of the authors, who have carefully reviewed and verified the manuscript to ensure its accuracy, originality, and compliance with ethical publication standards.

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