Detection of incipient faults in oil-immersed power transformers based on dissolved gas analysis: Case studies

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Abstract. Power transformers are one of the most crucial as well as costly equipment in power grids. Nowadays, a set of factors like the growing load, expanding power consumption, and market liberalization affect on the transformer reliability and operational lifetime. At present, numerous approaches are on hand to diagnosis and evaluate their operational conditions. Dissolved gas analysis (DGA) in the insulation oil is an efficient diagnostic scheme which can offer an essential source for transformer failure diagnosis. In this paper, five existing approaches of utilizing dissolved gas data to identify fault kind in power transformers oil are employed. The considered methods are: key gas technique, IEC 60599 technique, Doernenburg ratio scheme, Duval triangle framework, as well as Rogers ratio scheme. These fault diagnosis methods are used to interpret and validate the dissolved gas analysis (DGA) results for four case studies. The experiments are performed on four 15.75 kV/400 kV, 3-Phase, 250 MVA power transformers in a thermal power plant. The obtained DGA results reveal that all considered DGA methods have effectively detected the fault type for each considered case except Duval triangle method which has failed to discover the fault type for two cases.

1. Introduction
Power transformers are essential, critical as well as costly equipment in electric power networks [1]. These valuable assets undertake a primary responsibility in terms of supplying power at satisfactory voltage rates to consumers [2]. The abruption of the power transformers is too expensive and may cause a massive economic loss for the power companies [3]. In other words, transformer failures will likely give rise to a power outage. Thus, it is highly significant to detect rudimentary faults of power transformers as quickly as possible. In fact, transformer oil condition is a fundamental resource to diagnosis such kind of faults and can reflect the physical state of the transformer. Throughout failures and owing to electric stresses, oil decay arises. Consequently, a set of combustible gases that decrease the dielectric strength for the transformer oil can be generated and dissolved in oil [4].

Dissolved gas analysis (DGA) is one of the widely recognized schemes to identify possible power transformer rudimentary faults through sampling as well as scrutiny the insulation oil of transformers occasionally [5]. The key aim is to detect the dissolved combustible gases caused by such type of faults. There are a number of existing techniques for fault diagnosis of transformers by means of detection of dissolved gases.

In this article, five fault diagnosis methods have been employed to interpret and validate the DGA results for four case studies. These considered techniques are: key gas technique, IEC 60599 technique, Doernenburg ratio scheme, Duval triangle framework, as well as Rogers ratio scheme. The experiments have been performed on four 15.75 kV/400 kV, 3-Phase, 250 MVA power transformers...
in the Nasiriyah thermal power plant in Iraq. The remainder of this article is arranged as follows. Section 2 states the main utilized DGA schemes. Section 3 divulges the experimental results and discussions. Section 4 provides the main conclusions.

2. Dissolved gas analysis (DGA) schemes
DGA is a broadly utilized and international-recognized diagnostic technique for recognition of possible power transformer incipient failures [6, 7]. Also, it is a speedy and efficient tool for preventive conservation of power transformers. The DGA techniques used for sampling as well as checking the transformer insulating oil occasionally. The main aim is to recognize the basic gases decomposed in the oil owing to electric as well as thermal stresses [2, 7]. Consequently, transformer oil and insulation paper possibly decomposed and many gases are produced and settled in oil [5]. Actually, the important step in utilizing DGA for failure detection is properly diagnosing the failure that created the gases. The failure related gases generally released are CH$_4$, CO, C$_2$H$_2$, CO$_2$, C$_2$H$_6$, H$_2$, and C$_2$H$_4$. Consequently, if we predict the densities of the key gases in transformer oil in accordance with the new registered data, initial faults of transformer and its growth behavior can be discovered early, reducing the possibility of a transformer damage. There are a number of techniques for fault diagnosis of transformers by means of detection of dissolved gases. The mainly utilized are given below:

2.1. Key gas method
Key gases can be described as gases produced in oil-immersed power transformers which can be employed to recognize multifarious failure kinds, rooted in which gases are preponderant at different temperatures [8]. This technique imputes key gases (C$_2$H$_4$, H$_2$, C$_2$H$_2$, CO ) to fault kinds and seeks to detect four main failure kinds: partial discharge, arcing, thermal decomposition, and overheated cellulose. In fact, each failure in the transformer results in the germination of a specific key gas. The gas composition profile for this technique as well as relative proportions for the four common failure kinds is given in the IEEE Standard C57.104™-2008 [8]. Basically, this technique utilizes the total of the densities of burnable gases (i.e., C$_2$H$_4$, H$_2$, C$_2$H$_2$, CO, CH$_4$, as well as C$_2$H$_6$) and requires plotting all these gases as a percentage of their sum in a histogram.

2.2. Dornenburg ratio scheme
One of the most well-known gas ratio schemes is the Dornenburg Ratio Method [9]. This technique scrutinizes four gas ratios: C$_2$H$_6$/C$_2$H$_2$, C$_2$H$_2$/CH$_4$, C$_2$H$_2$/C$_2$H$_4$, as well as CH$_4$/H$_2$. These indexes can be utilized to recognize three major kinds of failures: electric arc, thermal decomposition, and partial discharge. This technique requires special gas concentrations (i.e., limiting concentrations) of the key gases to be applicable for fault diagnosis. These limits are presented in [8]. A comprehensive procedure of the Dornenburg Ratio Method is given in the IEEE Standard C57.104™-2008 [8]. The procedure involves a proposed faults diagnosis scheme based on special designated indexes for the key gases. One main drawback of this technique is the insufficient ratio ranges. Thus, such approach may encounter numerous "no interpretation".

2.3. Rogers ratio scheme
This approach pursues the similar process like the technique of Doernenburg, though, just three ratios are employed. Furthermore, unlike the Dornenburg Ratio Method, there is no reliance on the key gas concentration levels for a valid diagnosis [8]. This technique scrutinizes three gas ratios: C$_2$H$_6$/C$_3$H$_6$, C$_2$H$_2$/C$_3$H$_4$, as well as CH$_4$/H$_2$. A complete procedure of the Rogers Ratio Method is demonstrated in the IEEE Standard C57.104™-2008 [8]. The procedure engages a suggested failure judgment based on particular designated ratios for the key gases. Notably, this method is superior to the Dornenburg ratio method in terms of distinguishing more thermal failure kinds [3].
2.4. IEC 60599 method
This DGA technique is also based on the values of \( \text{C}_2\text{H}_4/\text{C}_2\text{H}_6 \), \( \text{C}_2\text{H}_2/\text{C}_2\text{H}_4 \), as well as \( \text{CH}_4/\text{H}_2 \). The entire procedure of this scheme is presented in the IEC Standard 60599 [10]. This scheme categorizes and recognizes transformer faults based on particular assigned ratios which are given in [2, 10]. The procedure involves a proposed strategy for fault diagnosis based on particular assigned ratios for the key gases [2].

2.5. Duval triangle approach
This DGA technique [11] explicates dissolved gases information by employing a triangle of relative percentage for three key gases: \( \text{C}_2\text{H}_2 \), \( \text{C}_2\text{H}_4 \), \( \text{CH}_4 \). A specific fault can be identified through estimating the entire concentration of the above mentioned gases. Then, dividing the amount of every gas by the sum in order to estimate the proportion of every gas. Figure 1 Demonstrates Duval’s triangle. It can be seen that six kinds of initial failures can be identified. Each fault kind is given a specific area.

![Duval triangle](image_url)

Figure 1. Duval triangle

3. Results and discussion
This section reveals the results of DGA. In this article, four cases are considered. The experiments have been performed on four 15.75 kV/400 kV, 3-Phase, 250 MVA power transformers (AT1, AT2, AT3, AT4) in the Nasiriyah thermal power plant in Iraq. First, a standard method namely, ASTM D923-15 [12] was used to sample insulation oil for each considered transformer. Then, the well-known standard test approach namely, ASTM D3612-02(2017) [13] was utilized to determine the concentrations of decomposed gases in the oil samples extracted. Table 1 reveals the results of DGA for the four tests considered in this study. Five fault diagnosis methods were utilized to interpret the DGA results shown in Table 1: key gas technique, IEC 60599 technique, Doernenburg ratio scheme, Duval triangle framework, as well as Rogers ratio scheme. Notably, the IEEE Standard C57.104™-2008 [8] was employed to distinguish fault kind for key gas technique.
3.1. Case study 1

Figure 2 shows the key gases estimation for Case 1 (i.e., AT1) using key gas method. Obviously, it can be noted that the principal dissolved gas in oil is H$_2$. A considerable quantity of CH$_4$ and small amounts of C$_2$H$_6$ and C$_2$H$_4$ are also detected. Thus, based on the IEEE Standard C57.104™-2008 [8], the fault type diagnosed is partial discharge (i.e., corona). Furthermore, it can be concluded that the fault engages discharges in cellulose owing to the sizeable amount of CO$_2$ formed in this case as revealed in Table 1. For further validation, Table 2 presents the failure kind diagnosis for the same case (i.e., AT1) using IEC 60599, Doernenburg ratio, and Rogers ratio methods. Observably, it can be noted that the ratios calculated from the DGA data fall within IEC, Doernenburg, and Rogers corresponding ratios designated to identify partial discharge. On the contrary, the detected fault type for this case using the Duval’s triangle method is thermal fault (T$_1$) as shown in Figure 3. To sum up, it can be noted that all considered DGA methods have effectively detected the fault type for this case (i.e., PD) except Duval triangle method which has failed to discover this fault type. Notably, the same drawback of Duval triangle method in terms of false diagnosis with the PD fault has been reported in [5].

Table 1. The results of DGA.

| Dissolved gas       | Concentration (ppm) |
|--------------------|---------------------|
|                    | Case 1  | Case 2  | Case 3  | Case 4  |
| Carbon Monoxide    | 26     | 12      | Not detected | 21     |
| Carbon Dioxide     | 3719   | 2847    | 2639    | 5011    |
| Ethylene           | 14     | 23      | 2303    | 119     |
| Hydrogen           | 2014   | 4107    | 50      | 407     |
| Acetylene          | 3      | 4       | 1       | 288     |
| Methane            | 196    | 366     | 413     | 56      |
| Ethane             | 74     | 144     | 47      | 52      |

Figure 2. Key gases estimation for case 1 (AT1)
3.2. Case study 2

Figure 4 demonstrates the key gases evaluation for Case 2 (i.e., AT2) by key gas method. Clearly, it can be noticed that the primary decomposed gas in oil is H$_2$. In addition, a sizeable magnitude of CH$_4$ and a little amount of C$_2$H$_6$ are detected. According to the IEEE Standard C57.104™-2008 [8], the fault type diagnosed is also partial discharge. For additional verification, table 3 displays the fault kind diagnosis for the same case (i.e., AT2) using IEC 60599, Doernenburg ratio, and Rogers ratio methods. Obviously, it can be seen that the ratios computed from the DGA data fall under IEC, Doernenburg, and Rogers corresponding ratios designated to recognize partial discharge. Meanwhile, the identified fault kind for this case using the Duval’s triangle method is also thermal fault (T$_1$) as illustrated in figure 5. Thus, Duval triangle method has failed to discover the fault type for this case.
Table 3. Fault Diagnosis for case 2 (AT2).

| Ratio          | Ratio calculated from DGA data | IEC ratios designated to identify partial discharge [2] | Doernenburg ratios designated to identify partial discharge [8] | Rogers ratios designated to identify partial discharge [2,8] |
|----------------|-------------------------------|------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
| R1= CH4/H2     | 0.089116143                   | < 0.1                                                | < 0.1                                                  | < 0.1                                                  |
| R2= C2H2/C2H4  | 0.1739130435                  | Not significant                                     | Not significant                                       | Not significant                                       |
| R3= C2H2/CH4   | 0.010928961                   | -                                                   | < 0.3                                                  | -                                                      |
| R4= C2H6/C2H2  | 36                            | -                                                   | > 0.4                                                  | -                                                      |
| R5= C2H4/C2H6  | 0.15972222222                 | < 0.2                                               | -                                                      | < 1                                                    |

Figure 4. Key gases estimation for case 2 (AT2).

Figure 5. Duval’s triangle for case 2 (AT2).
3.3. Case study 3

The key gases computation for this case using key gas method is shown in figure 6. Apparently, C\textsubscript{2}H\textsubscript{4} is the main decomposed gas in the oil. In addition, the key gases estimation shows a considerable quantity of CH\textsubscript{4} and tiny amounts of C\textsubscript{2}H\textsubscript{6} and H\textsubscript{2}. Consequently, it can be concluded that the fault type diagnosed is thermal decomposition [8]. Table 4 demonstrates the fault type identification for the same case (i.e., AT3) using the three considered ratio-based methods in this study. It is obvious that the ratios calculated from the DGA data fall within IEC and Rogers corresponding ratios designated to identify thermal fault > 700 °C. Furthermore, the DGA data ratios fall within Doernenburg corresponding ratios assigned to identify thermal decomposition. The identified fault kind for this case using the Duval’s triangle method is also thermal fault (T\textsubscript{3}) as illustrated in figure 7. Notably, the DGA results shown in table 1 displays a tiny amount of C\textsubscript{3}H\textsubscript{2}. Consequently, it can be concluded that this fault is not harsh and does not engages any electrical contacts.

**Figure 6.** Key gases estimation for case 3 (AT3).

**Table 4.** Fault diagnosis for case 3 (AT3).

| Ratio   | Ratio calculated from DGA data | IEC ratios designated to identify thermal fault > 700 °C [2] | Doernenburg ratios designated to identify thermal decomposition [8] | Rogers ratios designated to identify thermal fault > 700 °C [2,8] |
|---------|-------------------------------|-------------------------------------------------|-----------------------------------------------------|---------------------------------------------------------------|
| R\textsubscript{1}= CH\textsubscript{4}/H\textsubscript{2} | 8.26                           | > 1                                             | > 1                                                  | > 1                                                           |
| R\textsubscript{2}=C\textsubscript{2}H\textsubscript{2}/C\textsubscript{2}H\textsubscript{4} | 0.0004342                      | < 0.2                                          | < 0.75                                               | < 0.1                                                         |
| R\textsubscript{3}= C\textsubscript{2}H\textsubscript{2}/CH\textsubscript{4} | 0.0024213075                  | -                                              | < 0.3                                                | -                                                             |
| R\textsubscript{4}= C\textsubscript{2}H\textsubscript{4}/C\textsubscript{2}H\textsubscript{2} | 47                             | -                                              | > 0.4                                                | -                                                             |
| R\textsubscript{5}= C\textsubscript{2}H\textsubscript{4}/C\textsubscript{2}H\textsubscript{6} | 49                             | > 4                                            | -                                                    | > 3                                                           |
3.4. Case study 4
The key gases estimation for this case via the key gas technique is presented in figure 8. C\textsubscript{2}H\textsubscript{2} is the chief decomposed gas in the oil. Furthermore, the key gases estimation demonstrates a considerable quantity of H\textsubscript{2} and minor amounts of C\textsubscript{2}H\textsubscript{6}, C\textsubscript{2}H\textsubscript{4}, and CH\textsubscript{4}. It can be confirmed that the fault engages cellulose due to the considerable amount of CO\textsubscript{2} formed in this case as presented in table 1. Based on the IEEE Standard C57.104™-2008 [8], the fault type diagnosed in this case is electrical-arcing [8]. Table 5 displays the fault type recognition for this case (i.e., AT4) using the three considered ratio-based methods in this study. Once again, the ratios estimated from the DGA data fall within IEC, Doernenburg, and Rogers corresponding ratios designated to identify electrical-arcing. The detected fault kind for this case using the Duval’s triangle method is also electrical-arcing (D\textsubscript{2}) as illustrated in figure 8.
Table 5. Fault Diagnosis for case 4 (AT4).

| Ratio            | Ratio calculated from DGA data | IEC ratios designated to identify electrical-arcing [2] | Doernenburg ratios designated to identify electrical-arcing [8] | Rogers ratios designated to identify electrical-arcing [2,8] |
|------------------|--------------------------------|-------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------|
| R1= CH₄/H₂       | 0.1375921376                  | 0.1-1                                                  | > 0.1 to < 1                                                 | 0.1-1                                                     |
| R2= C₂H₆/C₂H₄    | 2.4201680672                  | 0.6-2.5                                               | > 0.75                                                       | 1-3                                                      |
| R3= C₂H₂/CH₄     | 5.1428571429                  | -                                                     | > 0.3                                                       | -                                                        |
| R4= C₂H₆/C₂H₄    | 0.18055555556                 | -                                                     | < 0.4                                                       | -                                                        |
| R5= C₂H₂/C₂H₆    | 2.2884615385                  | > 2                                                   | -                                                           | > 3                                                      |

4. Conclusions
In this study, five well-known fault diagnosis methods were utilized to explicate and certify the DGA results for four power transformers in service. The obtained DGA results disclose that all considered DGA methods have efficiently identified the fault category for each considered case except Duval triangle method. In fact, it can be confirmed that Duval triangle framework has a clear shortcoming in terms of false detection of PD faults. Notably, the fault type diagnosed for Case 4 power transformer (i.e., AT4) is electrical-arcing. Such fault requires an immediate maintenance to avoid total failure of this transformer. To sum up, timely DGA test would make the servicing engineers, establish more convinced judgments on the suitable maintenance and operation strategies. The outcomes of this study can offer background for electric power engineers in terms of using the appropriate DGA techniques for fault diagnosis.

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