Interpreting dissolved gases in transformer oil: A new method based on the analysis of labelled fault data

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Abstract
In this contribution, a new dissolved gas analysis (DGA) method combining key gases and ratio approaches for power transformer fault diagnostic is presented. It is based on studying subsets and uses the five main hydrocarbon gases including hydrogen (H2), methane (CH4), ethane (C2H6), ethylene (C2H4), and acetylene (C2H2). The proposed method uses 475 samples from the dataset divided into subsets formed from the maximum and minimum(s) concentrations of the whole dataset. It has been tested on 117 DGA sample data and validated on the International Electrotechnical Commission (IEC) TC10 database. The performance of the proposed diagnostic method was evaluated and compared with the following diagnostic methods: IEC ratios method, Duval’s triangle (DT), three ratios technique (TRT), Gouda’s triangle (GT), and self-organizing map (SOM) clusters. The results found were analysed by computer simulations using MATLAB software. The proposed method has a diagnosis accuracy of 97.42% for fault types, as compared to 93.16% of TRT, 96.58% of GT method, 97.25% of SOM clusters method and 98.29% of DT method. However, in terms of fault severity, the proposed method has a diagnostic accuracy of 90.59% as compared to 78.90% of SOM clusters method, 83.76% of TRT, 88.03% of DT method, and 89.74% of GT method.

1 | INTRODUCTION

Power transformers are the most expensive and important elements of power systems. They are crucial for the safety and stability of network operations. Indeed, the failure of a power transformer can lead to a major breakdown of the power grid, leading to outages, costly repairs and huge financial costs [1]. Therefore, early detection of transformer faults is imperative in the process of operating and maintaining power system networks. Chromatographic analysis of dissolved gas in oil, namely dissolved gas analysis (DGA) is one of the most widely used techniques for the early detection of faults inactive parts of transformers [2, 3]. Its popularity stems from the fact that this technique is non-intrusive and can be used for real-time monitoring. The principle of the method consists of periodically taking samples of transformer insulation oil to obtain the composition of gases dissolved in the oil due to the degradation of the insulation system [4]. Identification of the different dissolved gases is made possible by gas chromatography discovered in the 1940s [5]. Gas production is favoured by the temperature level and/or the energy produced by the fault. Depending on the type of fault, different types of decomposition processes may occur. When electrical or thermal faults occur in transformer oil, it degrades, generating combustible gases such as hydrogen (H2), methane (CH4), ethane (C2H6), ethylene (C2H4), and acetylene (C2H2). When decomposition occurs in cellulosic insulation, the gases generated are carbon monoxide (CO) and carbon dioxide (CO2), which indicates a thermal fault. Other gases such as oxygen (O2) and nitrogen (N2) are also produced [6]. Once the gases have been identified and quantified, the result still needs to be interpreted to assess the condition of the transformer. Several methods have been proposed in the literature to predict the occurrence of faults and to determine their types by interpreting the concentration of the gases detected [7]. Several standards from different committees and organizations, such as International Electrotechnical Commission (IEC) 60559-1999, Institute of Electrical and Electronics Engineers (IEEE) C57.104-1991, and International Council on Large Electric Systems (CIGRE) TF 15.01.01 provide guidelines for DGA interpretation.
Generally, conventional diagnostic methods using dissolved gases can be divided into three main categories: key gas, graphical and gas ratio methods [8]. The key gas method is based on the correlation of key gases generated with the fault type. In this method, the fault type is identified by the percentage of the generated gases as suggested by IEEE C57.104-2019 [9]. The graphical methods are based on a graphical representation visualizing the different types of faults. Each side of these graphs represents the relative proportions of key gases concentrations or combinations. The most popular graphical methods are Duval’s triangle (DT) [10] and Duval’s pentagon (DP) [11]. Other graphic methods exist in the literature such as Mansour’s pentagon [12], Gouda’s heptagon [13], or Gouda’s triangle (GT) [14]. Gas ratio methods are based on the correlation of ratio of fault gas concentrations with incipient fault types. These methods take into account the ratios of key gases to develop a code that is supposed to give an indication of fault type. These include, among others, Doernenburg’s ratios method (DRM) [15], Roger’s ratios method (RRM) [16], conventional IEC ratios method (IRM) [17], and three ratios technique (TRT) of Gouda et al. [18].

The conventional DGA methods of interpretation have certain drawbacks in terms of precision and uncertainty [19]. In order to overcome the difficulties posed by traditional methods in interpreting test results, a major effort has been made to develop intelligent diagnosis in this area. For this purpose, several methods have used artificial intelligence (AI) including expert system (EPS) [20], artificial neural network (ANN) [21–23], genetic algorithm (GA) [24], fuzzy logic theory [25–27], rough sets theory (RST) [28], Grey system theory (GST) [29], swarm intelligence (SI) algorithms [30, 31], data mining technology [32], self-organizing map (SOM) [33] and machine learning (ML) [34–36] for the diagnosis of transformer faults based on DGA data. The current existing conventional and intelligent methods are carried out by means of a sample dataset with the corresponding labelled faults. The size of the training data is a limitation for conventional methods because they require interpretation by human experts [37]. As a result, many of these techniques are based on a reduced amount of data, thus increasing the probability of misdiagnosis.

In this paper, a new diagnostic model combining key gas and gas ratio methods is proposed. It is based on multi-studying dataset (subset) and six ratios of H₂, CH₄, C₂H₆, C₂H₄, and C₂H₂. This method solves the problem of the size of the dataset by creating subsets made from combining maximum and minimum(s) sample concentrations of the main dataset. The ratio approach was used to distinguish between the different faults in each subset. The proposed diagnostic method was carried on using 475 samples dataset, tested on 117 samples DGA data. The classification performance of the proposed method is validated on IEC TC10 database and compared with following conventional methods DT, IRM, RRM, TRT, and DRM.

The remaining part of this paper is organized as follows: A brief description of the types of faults detectable by DGA, and the relationships between the gases produced and the corresponding faults is given in Section 2. Section 3 is devoted to brief review of gas ratio methods. The principle and the flow chart of proposed method are presented in Section 4. The test performance of proposed method and its comparison with conventional methods using IEC TC10 database are presented in Section 5. Finally, Section 6 concludes the paper.

2 | FAULT TYPES AND DGA

2.1 | Transformer fault types

The three major types of power transformer faults which can be reliably identified during a visual inspection are partial discharges, thermal overheating, and arcing [38]. Partial discharges and arcing refer to electrical faults and correspond to the deterioration of insulation due to high electrical stress. Thermal faults refer to the deterioration of the insulation system as a result of a rise in abnormal temperature. Such rises result from overheating of conductors, short circuits, overheating of windings due to Foucault’s currents, loose connections, and insufficient cooling [5]. Based on IEC 60599, these major fault types can be further classified into 6 types of transformer faults, summarized in Table 1.

| Acronyms | Faults |
|----------|--------|
| PD       | Partial discharge |
| D₁       | Low energy discharge |
| D₂       | High energy discharge |
| T₁       | Low temperature thermal fault $T < 300^\circ C$ |
| T₂       | Medium temperature thermal fault $300^\circ C < T < 700^\circ C$ |
| T₃       | High temperature thermal fault $T > 700^\circ C$ |

2.2 | Relationship between faults and dissolved gas produced

The two main causes of gas formation in an operating transformer are electrical and thermal stresses. Each type of fault degrades the oil or paper differently, each producing its amount of dissolved gas. The quantities are more or less important depending on the intensity of the particular fault. The nature of the gases formed and their relative proportions provide information on the type of stress, its intensity and the type of materials affected [39]. When an electric arc discharge occurs, large amounts of hydrogen and acetylene are produced, with minor amounts of methane and ethylene. For such a failure, acetylene typically accounts for 20% to 70% and hydrogen for 30% to 90% of the total hydrocarbons. Carbon dioxide and carbon monoxide can also be formed if the cellulose is present at the fault site. In some cases, the oil may carbonize [40]. The occurrence of thermal faults leads to the degradation of oil and paper. Oil overheating produces ethylene and methane with small amounts of hydrogen and ethane. Traces of acetylene can be formed if the fault is serious or involves electrical contacts. Large quantities of carbon dioxide and carbon monoxide are produced when thermal faults attack cellulose.

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Hydrocarbon gases, such as methane and ethylene, are formed if the fault involves an oil-impregnated structure [7].

3 | GAS RATIO METHODS

The gas ratio methods are conventional methods that use key gas ratios for fault diagnosis. In this section, a brief review of these methods is presented.

3.1 | Doernenburg’s ratio method

The DRM is the first method using the DGA approach. It was designed in 1794 in order to evaluate the three main faults types. Table 2 presents Doernenburg ratios according to the fault type and corresponding diagnostics. DRM is applied if the minimum concentration of one of H2, CH4, C2H6, and C2H2 gases exceeds twice limit values (Table 3) and one of the others gases exceeds the same limit values [41].

| Fault type               | Doernenburg ratios |
|-------------------------|--------------------|
| Thermal decomposition   | > 1.0, < 0.75, < 0.3, > 0.4 |
| Corona                  | < 0.1, /, < 0.3, > 0.4 |
| Arcing                  | 0.1–1.0, > 0.75, > 0.3, < 0.4 |

| Gas | H2 | CH4 | C2H6 | C2H4 | C2H2 | CO |
|-----|----|-----|------|------|------|----|
| Limit (ppm) | 100 | 120 | 65  | 50  | 1    | 350 |

3.2 | Roger’s ratio method

The Rogers Ratio Method takes into account the ratios of H2, CH4, C2H6, C2H4, and C2H2 to develop code allowing fault diagnosis. In Table 4, ratio range and corresponding codes are listed. The corresponding diagnostics for the various code combinations are presented in Table 5 [9].

| Ratio             | Ratio range                  | Code |
|-------------------|------------------------------|------|
| R1 = C2H2/C2H4    | R1 < 0.1                     | 0    |
| 0.1 ≤ R1 ≤ 3     | 1                            |     |
| R1 > 3            | 2                            |     |
| R2 = CH4/H2       | R2 < 0.1                     | 0    |
| 0.1 ≤ R2 ≤ 1     | 1                            |     |
| R2 > 1            | 2                            |     |
| R3 = C2H4/C2H6    | R3 < 1                       | 0    |
| 1 ≤ R3 ≤ 3       | 1                            |     |
| R3 > 3            | 2                            |     |

3.3 | IEC ratio method

The IEC ratio method takes into account the same ratios as DRM and the faults are classified into nine categories. The same codes of the three ratios in Table 4 are used in Table 6 which presents code combination according to the IRM faults diagnostics.

| Fault type                        | R1 | R2 | R3 |
|-----------------------------------|----|----|----|
| Normal                            | 0  | 0  | 0  |
| Partial discharges of low energy density | 1  | 0  | 0  |
| Partial discharges of high energy density | 1  | 1  | 0  |
| Discharges of low energy          | 0  | 1  | 2  |
| Discharges of high energy         | 0  | 1  | 2  |
| Thermal fault of low temperature < 150°C | 0  | 0  | 1  |
| Thermal fault of low temperature range 150–300°C | 2  | 0  | 0  |
| Thermal fault of medium temperature range 300–700°C | 2  | 0  | 1  |
| Thermal fault of high temperature range > 700°C | 2  | 0  | 2  |

3.4 | Three ratios technique

The TRT proposed by Gouda et al. [18] uses three new gas ratios to classify fault types and their severity, as shown in Table 7. In this method, the R1 ratio is used to classify thermal, arcing, and partial discharge faults. The R3 ratio, also used in the above diagnostic techniques, is used to separate thermal and electrical faults, and so it is used to confirm the type of R1 ratio fault. The R2 ratio is used to assess the degree of severity of thermal, electrical and partial discharge faults. It is used to distinguish between low (PD1) and high (PD2) partial discharge faults, low (D1) and high (D2) energy discharge faults and also very low (T0), low (T1), medium (T2) and high (T3) temperature thermal energy faults [14]. The corresponding diagnostics for the various code combinations, inspired by the flowchart described in [14], are presented in Table 8.
This technique shall be applied when at least one of the concentrations of dissolved gases exceeds the normal limits as shown in Table 9.

This article proposes a diagnostic method for power transformer faults that combines the key gas and gas ratio approaches. It is mainly based on the decomposition of the studying dataset into studying subsets which are then studied individually using the ratios method approach. Six gas ratios involving the five main hydrocarbon gases formed in transformer oil, namely \( H_2, CH_4, C_2H_6, C_2H_4, \) and \( C_2H_2 \) are used. The subsets obtained by decomposing the main dataset result from the combination of maximum and minimum(s) sample concentrations of the main dataset. The gas ratio approach is used to determine the different faults in each subset. As each subset is treated independently of the others, this allows more flexibility on the ratios to be taken into account and on the ratio ranges to be used for development of the model of each subset (sub-model). The final diagnostic model is obtained by combining the different sub-models obtained with each subset. Table 10 shows the subsets resulting from combinations having hydrogen as maximum concentration. A total of 75 studying subsets can be created from the main dataset. Table 11 lists the definition of the gas ratios used, while Figure 1 illustrates the principle of the proposed method.

### Table 7: Gouda codes

| Ratio | Ratio range | Code |
|-------|-------------|------|
| \( R_1 = \frac{C_2H_6 + C_2H_4}{H_2} \) | \( R_1 < 0.05 \) | 0 |
| | \( 0.05 \leq R_1 \leq 0.9 \) | 1 |
| | \( R_1 > 0.9 \) | 2 |
| \( R_2 = \frac{C_2H_4 + CH_4}{C_2H_6} \) | \( R_2 < 1 \) | 0 |
| | \( 1 \leq R_2 \leq 3.5 \) | 1 |
| | \( R_1 > 3.5 \) | 2 |
| \( R_3 = \frac{C_2H_6}{C_2H_4} \) | \( R_3 < 0.05 \) | 0 |
| | \( 0.05 \leq R_3 \leq 0.5 \) | 1 |
| | \( R_3 > 0.5 \) | 2 |

### Table 8: Fault diagnosis by TRT

| Fault type | Severity of fault | \( R_1 \) | \( R_2 \) | \( R_3 \) |
|------------|------------------|---------|---------|---------|
| High temperature thermal \( T > 700^\circ C \) | \( T_3 \) | 1 or 2 | 0 | 0 or 1 |
| Medium temperature thermal \( 300^\circ C < T < 700^\circ C \) | \( T_2 \) | 1 or 2 | 1 | 0 or 1 |
| Low temperature thermal \( 150^\circ C < T < 300^\circ C \) | \( T_1 \) | 1 or 2 | 1 | 0 or 1 |
| Low temperature thermal \( T < 150^\circ C \) | \( T_0 \) | 1 | / | 0 |

### Table 9: Limit concentrations of dissolved gases for the application of TRT [43]

| Gas      | \( H_2 \) | \( CH_4 \) | \( C_2H_6 \) | \( C_2H_4 \) | \( C_2H_2 \) | CO | \( CO_2 \) |
|----------|-----------|-----------|-------------|-------------|-------------|----|---------|
| Limit (ppm) | 100 | 120 | 65 | 50 | 1 | 350 | 2500 |

### Table 10: Possible studying subsets of \( H_2 \)

| Key gases concentrations | Maximum | Minimum(s) | Studying subsets |
|--------------------------|---------|------------|------------------|
| \( H_2 \) | | | \( H_2 \) |
| \( CH_4 \) | 1 |
| \( C_2H_6 \) | 2 |
| \( C_2H_4 \) | 3 |
| \( C_2H_2 \) | 4 |
| \( CH_4 \) & \( C_2H_6 \) | 5 |
| \( CH_4 \) & \( C_2H_4 \) | 6 |
| \( CH_4 \) & \( C_2H_2 \) | 7 |
| \( C_2H_6 \) & \( C_2H_4 \) | 8 |
| \( C_2H_6 \) & \( C_2H_2 \) | 9 |
| \( C_2H_4 \) & \( C_2H_2 \) | 10 |
| \( CH_4 \) & \( C_2H_6 \) & \( C_2H_4 \) | 11 |
| \( CH_4 \) & \( C_2H_6 \) & \( C_2H_2 \) | 12 |
| \( CH_4 \) & \( C_2H_4 \) & \( C_2H_2 \) | 13 |
| \( C_2H_6 \) & \( C_2H_4 \) & \( C_2H_2 \) | 14 |
| \( CH_4 \) & \( C_2H_6 \) & \( C_2H_4 \) & \( C_2H_2 \) | 15 |

### Table 11: Gas ratio used

| Ratio | Expression |
|-------|------------|
| \( R_1 \) | \( \frac{CH_4 + C_2H_6}{CH_4 + C_2H_4} \) |
| \( R_2 \) | \( \frac{CH_4 + C_2H_6}{CH_4 + C_2H_4} \) |
| \( R_3 \) | \( \frac{CH_4 + CH_4 + C_2H_4 + C_2H_6}{C_2H_6 + C_2H_2} \) |
| \( R_4 \) | \( \frac{CH_4 + CH_4 + C_2H_4 + C_2H_6}{C_2H_6 + C_2H_2} \) |
| \( R_5 \) | \( \frac{CH_4 + C_2H_6 + C_2H_4 + C_2H_2}{C_2H_6 + C_2H_2} \) |
| \( R_6 \) | \( \frac{C_2H_6 + C_2H_4}{C_2H_2} \) |

### 4 | PROPOSED METHOD FOR TRANSFORMERS FAULTS DIAGNOSTIC

#### 4.1 | Principle of the method

This article proposes a diagnostic method for power transformer faults that combines the key gas and gas ratio approaches. It is mainly based on the decomposition of the studying dataset into studying subsets which are then studied individually using the ratios method approach.
4.2 Example of application of the method

This example illustrates the application of the proposed method to a dataset of 25 samples (Table 12). The first step in the method is to create subsets from the samples in the studying dataset. In the second step, each subset is studied individually and the corresponding sub-model is proposed. The third and last step consists of grouping all the sub-models into a single program to have the diagnostic model. These three steps are presented in Figure 2. A generalization to a larger database made it possible to have the flowchart of the diagnostic method presented in Table B1 and the pseudo code in Appendix A. Examples of numerical application on samples 5 (purple), 10 (red), 17 (blue) and 25 (green) from Table 12 can be seen in Table B1.

5 RESULTS AND DISCUSSION

5.1 Data collection

The present study was carried out using 592 samples covering the six faults classes with actual fault types collected from several sources as presented in Table 13 below: 144 data samples from [44], 339 data samples collected from [45], 64 data samples from [19], 20 data from tab. 2 of [46] and 25 data from tab. 1 and 2 of [47].

In order to conduct the new proposed method, the DGA data was divided into studying and testing dataset as shown in Table 14. The studying dataset is composed of samples labelled of dissolved gas and is used for the implementation of flowchart of the proposed method. The testing dataset is used for verification of observations made in each subset.

5.2 Results and discussion

Implementation of the proposed method was performed using MATLAB software and the algorithm was programmed in .m codes. Table 15 presents an overview of the fault diagnostic accuracy obtained by comparing studying and testing datasets.

Considering the diagnostic accuracy results obtained from the studying dataset, it is clear that the proposed method performs better at detecting PD, D2 and T3 faults, with accuracy greater than or equal to 90%. A fairly good accuracy, close to 70%, was reported for faults D1 and T2 while an accuracy of 82.6% was assigned for fault T1. In summary, 83.36% of the dissolved gas samples were well diagnosed, i.e. 396 out of 475...
FIGURE 2  Example of application of the steps of the proposed method

TABLE 13  Distribution of collected data according to references

| Ref. | PD | D1 | D2 | T1 | T2 | T3 | Total |
|------|----|----|----|----|----|----|-------|
| [44] | 16 | 35 | 15 | 29 | 19 | 30 | 144   |
| [45] | 32 | 51 | 74 | 85 | 41 | 56 | 339   |
| [19] | 0  | 32 | 32 | 0  | 0  | 0  | 64    |
| [46] | 7  | 2  | 2  | 0  | 5  | 4  | 20    |
| [47] | 0  | 7  | 18 | 0  | 0  | 0  | 25    |
| Total| 55 | 127| 141| 114| 65 | 90 | 592   |

TABLE 14  Composition of studying and testing dataset

| Fault types | PD | D1 | D2 | T1 | T2 | T3 | Total |
|-------------|----|----|----|----|----|----|-------|
| Studying dataset | 44 | 102| 113| 92 | 52 | 72 | 475   |
| Testing dataset  | 11 | 25 | 28 | 22 | 13 | 18 | 117   |
| Total         | 55 | 127| 141| 114| 65 | 90 | 592   |

TABLE 15  Fault diagnosis accuracy

| Fault diagnosis accuracy (%) | PD | D1 | D2 | T1 | T2 | T3 | Total |
|------------------------------|----|----|----|----|----|----|-------|
| Studying dataset            | 90.90 | 72.54 | 90.26 | 82.60 | 71.15 | 93.05 | 83.36 |
| Testing dataset             | 90.90 | 84  | 96.42 | 72.72 | 100 | 94.44 | 88.88 |

data sets. Based on the diagnostic accuracies obtained from the testing dataset, it appears that the observations made on the studying dataset were well carried out in the measure that its diagnostic precision was higher.

5.3  Validation and comparison with other conventional methods using IEC TC10 database

The IEC TC 10 database contains 117 cases of fault for transformers in service, which were identified by visual inspection [38]. This data is not part of the new DGA proposed method. In order to validate this proposed model, this DGA database was used. The diagnostic results are presented in Table C1 and the average diagnostic accuracies by equipment type are summarized in Table 17.

Table 16 shows the equipment’s abbreviations of the IEC TC10 database. In Table 17, the fault types refer to the three

TABLE 16  Abbreviations used for equipment type

| Abbreviations | Equipment       |
|---------------|-----------------|
| P             | Power transformer without communication OLTC |
| U             | Power transformer with communication OLTC |
| R             | Reactor         |
| I             | Instrument transformer |
| B             | Bushing         |
| C             | Cable           |
main faults, i.e. partial discharges, thermal overheating, and arcing. As for severity, it refers to the three main faults: i.e. PD for partial discharge, D₁ and D₂ for arcing, and T₁, T₂ and T₃ for thermal overheating. The results obtained are compared with those obtained with IRM [16], DT [10], TRT [18], GT [14] and SOM clusters [33].

Tables 18 and 19 summarize the comparison between proposed diagnostic method and other diagnostic methods obtained with 117 cases of IEC TC10 databases.

The diagnostic accuracies with the IEC TC10 database for the different methods are presented in terms of the equipment and distributed according to severity and fault type. Considering the diagnostic accuracy obtained from the equipment, the proposed method could be used to detect and classify faults in P, U, R, I, and C equipment. For power transformers without communicating OLTC, the proposed method has diagnostic accuracy of 88.88% and 97.22% respectively in terms of severity and fault type. However, for power transformers with communicating OLTC, the diagnostic accuracy is 100% for both types. Out of the 117 cases including all equipment, the proposed method has diagnostic accuracy of 90.60% and 97.43% for severity and fault type respectively.

The use of subsets makes it possible on the one hand to propose empirical methods to diagnose power transformers using a large number of labelled data and on the other hand to take into account all the characteristics of the sample subsets created. However, the multiplication of studying datasets increases the work of the human expert, who no longer confines himself to observations allowing detection and classification of faults in a single set, but in several sets at the same time. Although the new diagnostic method is more constraining in terms of the work carried out, it offers several avenues for improving the performance of existing methods. Also, it can be used to propose a method with dynamic ratios according to the different subsets created. It could even be used to combine several methods into one by applying them to the different subsets created.

6 | CONCLUSION

In this paper, a new conventional DGA method for fault diagnosis of power transformers is proposed. This method is based on multi datasets combining the key gases and gas ratio approaches. The key gases approach is used to form the different studying subsets from the combination of maximum and
minimum(s) sample gas concentration of main dataset. The gas ratio approach is used to detect and classify faults of each studying subset. The dataset used in this paper contains 709 labelled samples covering six fault types. The first group of 592 samples is used for the implementation and evaluation of the diagnostic model proposed. Taking into account the subjectivity of the testing dataset, the performance of proposed diagnostic model was validated using the second group of data consisting of the 117 samples from the IEC TC10 database. The proposed method has a diagnosis accuracy of 97.42% for fault types, as compared to 93.16% of TRT, 96.58% of GT method, 97.25% of SOM clusters method, and 98.29% of DT method. In terms of fault severity, however, the proposed method has the highest diagnostic accuracy of 90.60% compared to 78.90% of SOM clusters method, 83.76% of TRT, 88.03% of DT method and 89.74% of GT method. The main advantage of the proposed method is that it can be formalized insofar as the schematic approach is clear and comprehensible. Whereas this is not the case with the conventional methods existing in the literature, which present their flow chart without the methodical approach that made it possible. The use of studying subsets makes it possible to implement conventional diagnostic methods using large databases leading to the proposal of a more efficient diagnostic model. In addition, it offers many possibilities in the improvement of existing conventional methods, in the implementation of combined or even hybrid diagnostic approaches. The proposed model appears to be a promising approach to support a new generation of DGA diagnosis and to overcome the complexities.

REFERENCES

1. Yang, Z., et al.: Association rule mining-based dissolved gas analysis for fault diagnosis of power transformers. IEEE Trans. Syst., Man, Cybern. C 39(6), 597–610 (2009)
2. Sun, H.-C., et al.: A review of dissolved gas analysis in power transformers. Energy Procedia 14, 1220–1225 (2012)
3. Wani, S.A., et al.: Smart diagnosis of incipient faults using dissolved gas analysis-based fault interpretation matrix (FIM). Arab. J. Sci. Eng. 44(8), 6977–6985 (2019)
4. Zhang, Y., et al.: Power transformer fault diagnosis considering data imbalance and data set fusion. High Voltage 1–12 (2020)
5. Senoussaoui, M.E.A.: Contribution des techniques intelligentes au diagnostic industriel des transformateurs de puissance. Thesis, Université DJILILLI LIABBES DE SIDI BEL ABBES (2019)
6. Bustamante, S., et al.: Dissolved gas analysis equipment for online monitoring of transformer oil. A review. Sensors 19(19), 4057 (2019)
7. Cheng, L., Yu, T.: Dissolved gas analysis principle-based intelligent approaches to fault diagnosis and decision making for large oil-immersed power transformers: A survey. Energies 11(4), 913 (2018)
8. Taecharoen, P., Kunagonnyomrattana, P., Chatigo, S.: Development of dissolved gas analysis analyzing program using visual studio program. In: 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), pp. 785–790. IEEE (2019)
9. IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers. IEEE (2019)
10. Duval, M.: Fault gases formed in oil-filled breathing E.H.V. power transformers—The interpretation of gas analysis data. IEEE Pap, 1–4 (1974)
11. Duval, M., Lamarre, L.: The duval pentagon—A new complementary tool for the interpretation of dissolved gas analysis in transformers. IEEE Electr. Insul. Mag. 30(6), 9–12 (2014)
12. Mansour, D.-E.A.: Development of a new graphical technique for dissolved gas analysis in power transformers based on the five combustible gases. IEEE Trans. Dielectr. Electr. Insul. 22(5), 2507–2512 (2015)
13. Gouda, O.E., El-Hoshy, S.H., El-Tamaly, H.H.: Proposed heptagon graph for DGA interpretation of oil transformers. IET Gener. Transm. Distrib. 12(2), 490–498 (2018)
14. Gouda, O.E., El-Hoshy, S.H., El-Tamaly, H.H.: Condition assessment of power transformers based on dissolved gas analysis. IET Gener. Transm. Distrib. 13(12), 2299–2310 (2019)
15. IEEE Guide for the Detection and Determination of Generated Gases in Oil-Immersed Transformers and Their Relation to the Serviceability of the Equipment. ANSI/IEEE (1978)
16. Rogers, R.: IEEE and IEC codes to interpret incipient faults in transformers, using gas in oil analysis. IEEE Trans. Electr. Insul. EI-13(3), 349–354 (1978)
17. Interpretation of the analysis of gases in transformers and other Oil filled electrical equipment’s in service. IEC Publication 60599 (1999)
18. Gouda, O.E., El-Hoshy, S.H., El-Tamaly, H.H.: Proposed three ratios technique for the interpretation of mineral oil transformers dissolved gas analysis. IET Gener. Transm. Distrib. 12(11), 2650–2661 (2018)
19. Illias, H.A., Liang, W.Z.: Identification of transformer fault based on dissolved gas analysis using hybrid support vector machine-modified evolutionary particle swarm optimisation. PLoS One 13(1), e0191366 (2018)
20. Nagpal, T., Brar, Y.S.: Artificial neural network approaches for fault classification: Comparison and performance. Neural Comput. Appl. 25(7–8), 1863–1870 (2014)
21. Ghoneim, S.M., Taha, I.B.M., Elkalahsy, N.I.: Integrated ANN-based proactive fault diagnostic scheme for power transformers using dissolved gas analysis. IEEE Trans. Dielectr. Electr. Insul. 23(3), 1838–1845 (2016)
22. Yang, X., et al.: BA-PNN-based methods for power transformer fault diagnosis. Adv. Eng. Inf. 39, 178–185 (2019)
23. Du, H., Wang, G., Li, J.: Transformer fault identification with an IF-1DCNN based on informative integration of heterogeneous sources. Math. Probl. Eng. 2021, 1 (2021)
24. Kari, T., et al.: Hybrid feature selection approach for power transformer fault diagnosis based on support vector machine and genetic algorithm. IET Gener. Transm. Distrib. 12(21), 5672–5680 (2018)
25. Abu-Siada, A., Hmood, S.: A new fuzzy logic approach to identify power transformer criticality using dissolved gas-in-oil analysis. Int. J. Electr. Power Energy Syst. 67, 401–408 (2015)
26. Noon, M., Effatnejad, R., Hajhosseini, P.: Using dissolved gas analysis results to detect and isolate the internal faults of power transformers by applying a fuzzy logic method. IET Gener.Transm. Distrib. 11(10), 2721–2729 (2017)
27. Poonmoy, N., Suwanasri, C., Suwanasri, T.: Fuzzy logic approach to dissolved gas analysis for power transformer failure index and fault identification. Energies 14(1), 36 (2021)
28. Shaaban, S.M., Nabawy, H.A.: Transformer fault diagnosis method based on rough set and generalized distribution table. Int. J. Intelligent Eng. Syst. 5(2), 17–24 (2012)
29. Xue, M.: State evaluation for transformer based on grey system theory. Appl. Mech. Mater. 488-489, 983–987 (2014)
30. Mo, W., et al.: Power transformer fault diagnosis using support vector machine and particle swarm optimization. In: 2017 10th International Symposium on Computational Intelligence and Design (ISCID), pp. 511–515. IEEE (2017)
31. Cao, Z., et al.: Application of particle swarm optimization algorithm in power transformer fault diagnosis. J. Phys. Conf. Ser. 1624, 042022 (2020)
APPENDIX A: PSEUDO CODE

1. Input dissolved gas sample concentrations
2. Compute the gas ratios R₁ to R₆ (Table 11)
3. Compute total dissolved gas sample concentrations
   \[ T = H₂ + CH₄ + C₂H₆ + C₂H₄ + C₂H₂; \]
4. Determination of maximum and minimum(s) sample concentrations
   \[ C_{\text{max}} = \max([H₂, CH₄, C₂H₆, C₂H₄, C₂H₂]); \]
   \[ C_{\text{min}} = \min([H₂, CH₄, C₂H₆, C₂H₄, C₂H₂]); \]
5. Determination of subsets

\[
\text{if } C_{\text{max}} = = H₂ \\
\text{if } C_{\text{min}} = = CH₄ \\
\text{N} = \text{SM}₁; \\
\text{else if } C_{\text{min}} = = C₂H₆ \\
\text{N} = \text{SM}₂; \\
\text{else if } C_{\text{min}} = = C₂H₄ \\
\text{N} = \text{SM}₃; \\
\text{else if } C_{\text{min}} = = C₂H₂ \\
\text{N} = \text{SM}₄; \\
\text{else if } C_{\text{min}} = = CH₄ \& C₂H₆ \\
\text{N} = \text{SM}₅; \\
\text{⋮} \\
\text{else if } C_{\text{min}} = = CH₄ \& C₂H₄ \& C₂H₂ \\
\text{N} = \text{SM}₁₅; \\
\text{end} \\
\text{elseif } C_{\text{max}} = = CH₄ \\
\text{if } C_{\text{min}} = = H₂ \\
\text{N} = \text{SM}₁₆; \\
\text{else if } C_{\text{min}} = = C₂H₆ \\
\text{N} = \text{SM}₁₇; \\
\text{⋮} \\
\text{else if } C_{\text{min}} = = H₂ \& CH₄ \& C₂H₄ \& C₂H₂ \\
\text{N} = \text{SM}₃₀; \\
\text{end} \\
\text{elseif } C_{\text{max}} = = C₂H₆ \\
\text{if } C_{\text{min}} = = H₂ \\
\text{N} = \text{SM}₁₇; \\
\text{else if } C_{\text{min}} = = CH₄ \\
\text{N} = \text{SM}₃₂; \\
\text{⋮} \\
\text{else if } C_{\text{min}} = = H₂ \& CH₄ \& C₂H₄ \& C₂H₂ \\
\text{N} = \text{SM}₄₅; \\
\text{end} \\
\text{elseif } C_{\text{max}} = = C₂H₄ \\
\text{if } C_{\text{min}} = = H₂ \\
\text{N} = \text{SM}₄₆; \\
\text{else if } C_{\text{min}} = = CH₄ \\
\text{N} = \text{SM}₄₇; \\
\text{⋮} \]

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APPENDICES

The pseudo code describes step by step how the method can be reproduced by everyone. In this pseudo code, it is indicated how the flowchart can be transformed into a code with two examples. Table B1 presents the flow chart of the proposed diagnostic method and Table C1 shows the diagnostic results obtained with the conventional methods and the proposed method, using IEC TC10 database.
elseif $C_{\text{min}} = \text{H}_2 \& \text{CH}_4 \& \text{C}_2\text{H}_6 \& \text{C}_2\text{H}_4$
    \quad N = \text{SM75};
    \end{end}
\end{end}

6. Construction of the model

Switch $N$

    case SM1
        if $R_1 \leq 0.15$
            disp('Low energy discharge: D1')
        \quad \text{end}
    \else
        \end{end}
\end{end}

\end{end}

\end{end}
### TABLE B1  Flow chart of the proposed diagnostic model of power transformers

| Key Gases | Ratios | Concentration | Fault type |
|-----------|--------|---------------|------------|
| Max.      | Minimum (s) | R₁  | R₂  | R₃  | R₄  | R₅  | R₆  | T   | C₂H₆ | PD | D₁ | D₂ | T₁ | T₂ | T₃ |
| CH₄       | <0.15  | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | >0.15  | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₂H₆      | ≥0.20  | x   | x   | ≥0.10 | ≥0.65 | x   | x   | x   | ≥4   |    |    |    |    |    |    |
|           | <0.20  | x   | x   | <0.10 | x   | x   | x   | x   | <4   |    |    |    |    |    |    |
|           | <0.23  | x   | x   | <0.40 | ≥0.45 | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | ≥0.10 | <0.65 | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | ≥0.20 | <0.65 | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.20 | <0.10 | ≥0.40 | <0.45 | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | <0.40 | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₂H₄      | x   | <0.15 | x   | x   | ≥0.05 | x   | x   | x   | <0.40 |    |    |    |    |    |    |
|           | x   | >0.15 | x   | x   | ≥0.05 | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.15 | x   | x   | <0.05 | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | ≥0.15 | >1   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | ≥0.15 | <1   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.15 | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | ≤1   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.45 | x   | x   | ≥0.75 | >0.75 | x   | x   | x   |      |    |    |    |    |    |    |
|           | >0.45 | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | ≥0.15 | ≥0.15 | [0.1:0.15] | ≤15 | x   | x   | x   |      |    |    |    |    |    |    |
|           | ≥0.15 | <0.15 | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.15 | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₄H₄      | x   | >0.15 | >0.15 | ≤0.15 | ≤0.05 | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | <0.15 | >0.15 | >0.05 | >0.05 | x   | x   | x   |      |    |    |    |    |    |    |
|           | x   | >0.15 | >0.15 | >0.05 | >0.05 | x   | x   | x   |      |    |    |    |    |    |    |
| H₂        | x   | ≥0.15 | ≥0.15 | ≤0.15 | ≤0.05 | x   | x   | x   |      |    |    |    |    |    |    |
|           | ≥0.15 | <0.15 | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.15 | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | ≥0.15 | ≥0.15 | ≤0.15 | ≤0.05 | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | ≤0.15 | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | >0.15 | ≥0.15 | ≥0.15 | ≤0.15 | ≤0.05 | x   | x   | x   |      |    |    |    |    |    |    |
|           | <0.15 | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
|           | >0.15 | ≥0.15 | ≥0.15 | ≤0.15 | ≤0.05 | x   | x   | x   |      |    |    |    |    |    |    |
| CH₄ & C₂H₆| x   | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₂H₆ & C₂H₄| x   | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₂H₆ & C₂H₂| x   | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₂H₄ & C₂H₂| x   | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |
| C₂H₆ & C₂H₄ & C₂H₂| x   | x   | x   | x   | x   | x   | x   | x   |      |    |    |    |    |    |    |

(Continues)
|                | <0.15 | ≥0.55 | <1500 | ≥1500 | <0.05 | ≥0.05 | <1000 | ≥1000 |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| <0.4           | x     | x     |       |       |       |       |       |       |
| x              |       |       | x     | x     |       |       |       |       |
| ≥0.60          |       |       |       | x     | x     |       |       |       |
| ≤0.90          |       |       |       |       |       |       |       |       |
| ≥0.25          |       |       |       |       |       |       |       |       |
| <0.25          |       |       |       |       |       |       |       |       |
| ≥0.775         |       |       |       |       |       |       |       |       |
| <0.60          |       |       |       |       |       |       |       |       |
| ≥0.775         |       |       |       |       |       |       |       |       |

| H₂ & C₂H₄      | x     | x     | x     | x     |       |       |       |       |
| H₂ & C₂H₅      | x     | x     | x     | x     |       |       |       |       |
| C₂H₄ & C₃H₆    | x     | x     | x     |       | x     |       |       |       |
| H₂ & C₂H₄ & C₂H₅ | x | x | x | x | x | x | x | x |
| TABLE B1 (Continued) |
|-----------------------|
|                       | H₂ & C₃H₆ & C₂H₂ | H₂ & CH₄ & C₃H₆ & C₂H₂ | H₂ & CH₄ | CH₄ & C₂H₆ | C₂H₂ & C₃H₄ | C₂H₂ & C₃H₄ | H₂ & C₂H₆ & C₂H₄ | CH₄ & C₂H₆ & C₃H₄ |
| H₂                    | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| CH₄                   | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| C₂H₂                  | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| C₂H₄                  | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| H₂ & CH₄              | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| CH₄ & C₂H₆            | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| C₂H₂ & C₃H₄           | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| H₂ & C₂H₆ & C₂H₄      | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| CH₄ & C₂H₆ & C₃H₄     | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x | x x x x x x x x |
| H₂  | CH₄ | C₂H₆ | C₂H₄ | C₂H₂ | Equip. | Act.  | IRM | DT | TRT | GT | SOM | Prop. |
|-----|-----|------|------|------|--------|------|-----|----|-----|----|-----|-------|
| 57  | 24  | 27   | 30   | 0    | B      | D1   | D2  | D2 | D2  | D2 | D2  | D2    |
| 1000| 500 | 400  | 500  | 0    | B      | D1   | D2  | D2 | D2  | D2 | D2  | D2    |
| 8266| 1061| 22   | 0,001| 0,001| B      | PD   | ND  | PD | PD  | PD | PD  | PD    |
| 0,001|18900|410  | 540  | 330  | B      | T₁/T₂| ND  | T₁ | T₁  | T₁ | T₁/T₂| T₁    |
| 40000|400  | 70   | 600  | 6    | B      | T₁/T₂| ND  | T₁ | T₁  | T₁ | T₁/T₂| PD    |
| 210 | 22  | 6    | 6    | 7    | C      | D1   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 150 | 130 | 9    | 55   | 30   | C      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 7940| 2000| 355  | 3120 | 5390 | I      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 33046|619 | 58   | 2    | 0,001| I      | PD   | PD  | PD | PD  | PD | PD  | PD    |
| 92600|10200|0,001| 0,001| 0,001| I      | PD   | D₁  | PD | PD  | PD | PD  | PD    |
| 9340| 995 | 60   | 6    | 7    | I      | PD   | ND  | PD | PD  | PD | PD  | PD    |
| 26788|18342|2111 | 27   | 0,001| I      | PD   | NF  | PD | T₁  | PD | PD  | PD    |
| 36036|4704| 554  | 5    | 10   | I      | PD   | ND  | PD | PD  | PD | PD  | PD    |
| 37800|1740| 249  | 8    | 8    | I      | PD   | PD  | PD | PD  | PD | PD  | PD    |
| 40280|1069| 1060 | 1    | 1    | I      | PD   | PD  | PD | PD  | PD | PD  | PD    |
| 360 | 610 | 259  | 260  | 9    | I      | T₁/T₂| T₂  | T₂ | T₂  | T₂ | T₁/T₂| T₂    |
| 960 | 4000| 1290 | 1560 | 6    | I      | T₁/T₂| T₂  | T₂ | T₂  | T₂ | T₁/T₂| T₂    |
| 1   | 27  | 49   | 4    | 1    | I      | T₁/T₂| ND  | T₁ | NF  | N  | T₁/T₂| T₁    |
| 24700|61000|26300| 42100| 1560 | I      | T₁/T₂| T₂  | T₂ | T₂  | T₂ | T₁/T₂| T₂    |
| 305 | 100 | 33   | 161  | 541  | P      | D₁   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 595 | 80  | 9    | 89   | 244  | P      | D₁   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 78  | 20  | 11   | 13   | 28   | P      | D₁   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 95  | 10  | 0,001| 11   | 39   | P      | D₁   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 645 | 86  | 13   | 110  | 317  | P      | D₁   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 1230| 163 | 27   | 233  | 692  | P      | D₁   | D₁  | D₁ | D₁  | D₁ | D₁  | D₁    |
| 1330| 10  | 20   | 66   | 182  | P      | D₁   | ND  | D₂ | D₂  | D₂ | D₂  | D₁    |
| 75  | 15  | 7    | 14   | 26   | P      | D₂   | D₁  | D₂ | D₂  | D₂ | D₂  | D₁    |
| 1820| 405 | 35   | 365  | 634  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 60  | 5   | 2    | 21   | 21   | P      | D₂   | ND  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 2770| 660 | 54   | 712  | 763  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 260 | 215 | 35   | 334  | 277  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 440 | 89  | 19   | 304  | 757  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 545 | 130 | 16   | 153  | 239  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 755 | 229 | 32   | 404  | 460  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 1170| 255 | 18   | 312  | 325  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 1500| 395 | 28   | 395  | 323  | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 1570| 1110| 175  | 1780 | 1830 | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 7150| 1440| 97   | 1210 | 1760 | P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 20000|13000|1850 | 29000| 57000| P      | D₂   | D₂  | D₂ | D₂  | D₂ | D₂  | D₂    |
| 3090| 5020| 323  | 3800 | 2540 | P      | D₂   | ND  | D₂  | D₂  | D₂  | D₂    |
| 3700| 1690| 128  | 2810 | 3270 | P      | D₂   | D₂  | D₂ | D₂  | D₂  | D₂    |
| 12  | 18  | 4    | 4    | 0,001| P      | T₁/T₂| T₂  | T₁ | NF  | T₁ | T₁/T₂| T₁    |
| 14  | 44  | 1    | 1    | 1    | P      | T₁/T₂| ND  | T₁ | T₁  | T₁ | T₁/T₂| T₁    |
| 48  | 610 | 29   | 10   | 0,001| P      | T₁/T₂| T₁  | PD | T₁  | PD | T₁/T₂| T₁    |
| 66  | 60  | 2    | 7    | 0,001| P      | T₁/T₂| ND  | T₁ | NF  | N  | T₁/T₂| PD    |
| $H_2$ | $CH_4$ | $C_2H_4$ | $C_2H_6$ | $C_2H_2$ | Equip. | Act. | IRM | DT | TRT | GT | SOM | Prop. |
|------|--------|---------|---------|---------|--------|-----|-----|-----|-----|----|-----|------|
| 1270 | 3450   | 520     | 1390    | 8       | P      | T1/T2| T2  | T2  | T2  | T2 | T1/T2| T2  |
| 3420 | 7870   | 1500    | 6990    | 33      | P      | T1/T2| T1  | T3  | T2  | T2 | T1/T2| T3  |
| 6    | 2990   | 29990   | 26076   | 67      | P      | T3   | T1  | T3  | T3  | T3 | T3   | T3  |
| 107  | 143    | 34      | 222     | 2       | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 400  | 940    | 210     | 820     | 24      | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 290  | 966    | 299     | 1810    | 57      | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 290  | 1260   | 231     | 820     | 8       | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 2500 | 10500  | 4790    | 13500   | 6       | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 6709 | 10500  | 1400    | 17700   | 750     | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 8800 | 64064  | 72128   | 95650   | 0.001   | P      | T3   | T3  | T3  | T3  | T3 | T3   | T3  |
| 60   | 10     | 4       | 4       | 4       | R      | D1   | D1  | D1  | D2  | D1 | D1   | D1  |
| 385  | 60     | 8       | 53      | 159     | R      | D1   | D2  | D1  | D1  | D1 | D1   | D1  |
| 1790 | 580    | 321     | 336     | 619     | R      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |
| 120  | 25     | 1       | 8       | 40      | R      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |
| 2177 | 1049   | 207     | 440     | 705     | R      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |
| 4230 | 690    | 5       | 196     | 1180    | R      | D1   | D1  | D1  | D1  | PD | D1   | D1  |
| 6454 | 2313   | 121     | 2159    | 6432    | R      | D1   | D2  | D1  | D1  | D1 | D1   | D1  |
| 7600 | 1230   | 318     | 836     | 1560    | R      | D1   | D2  | D2  | D2  | D2 | D2   | D2  |
| 90   | 28     | 8       | 31      | 32      | R      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |
| 4419 | 3564   | 668     | 2861    | 2025    | R      | D2   | D2  | D2  | D2  | D2 | D2   | T3  |
| 5000 | 1200   | 83      | 1000    | 1100    | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 99   | 170    | 20      | 200     | 190     | R      | D2   | ND  | D2  | D2  | D2 | D2   | D2  |
| 110  | 62     | 90      | 140     | 250     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 120  | 31     | 0.001   | 66      | 94      | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 220  | 77     | 22      | 170     | 240     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 245  | 120    | 18      | 131     | 167     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 305  | 85     | 25      | 197     | 130     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 530  | 345    | 85      | 266     | 250     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 535  | 160    | 16      | 305     | 680     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 810  | 580    | 111     | 570     | 490     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 1900 | 530    | 35      | 383     | 434     | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 2800 | 2800   | 234     | 3500    | 3600    | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 5100 | 1430   | 0.001   | 1140    | 1010    | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 5900 | 1500   | 68      | 1200    | 2300    | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 8200 | 3790   | 250     | 4620    | 5830    | R      | D2   | D2  | D2  | D2  | D2 | D2   | D2  |
| 480  | 1075   | 298     | 1132    | 0.001   | R      | T1/T2| T1  | T3  | T3  | T3 | T1/T2| T3  |
| 2031 | 149    | 20      | 3       | 0.001   | R      | T1/T2| PD  | PD  | PD  | PD | T1/T2| PD  |
| 1    | 8      | 8       | 100     | 6       | R      | T1   | T1  | T1  | T1  | T1 | T2   | T1  |
| 12705| 23498  | 6047    | 34257   | 5188    | R      | T3   | ND  | T3  | T3  | T3 | T3   | T3  |
| 300  | 700    | 280     | 1700    | 36      | R      | T3   | T1  | T3  | T3  | T3 | T2   | T3  |
| 1550 | 2740   | 816     | 5450    | 184     | R      | T3   | T1  | T3  | T3  | T3 | T3   | T3  |
| 3910 | 4290   | 626     | 6040    | 1230    | R      | T3   | ND  | T3  | T3  | T3 | T3   | T3  |
| 4    | 1      | 2       | 7       | 52      | U      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |
| 543  | 120    | 41      | 411     | 1880    | U      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |
| 1900 | 285    | 31      | 957     | 7730    | U      | D1   | D1  | D1  | D1  | D1 | D1   | D1  |

(Continues)
| H₂ | CH₄ | C₂H₆ | C₂H₄ | Equip. | Act. | IRM | DT | TRT | GT | SOM | Prop. |
|----|-----|------|------|--------|------|-----|----|-----|----|-----|-------|
| 13 | 3   | 1    | 3    | 6     | U    | D₂  | D₁ | D₂  | D₂ | D₂  | D₁   | D₂   |
| 10000 | 6730 | 345  | 7330 | 10400 | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 13500 | 6110 | 212  | 4510 | 4040  | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 34 | 21  | 4    | 49   | 56    | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 157 | 67  | 7    | 53   | 104   | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 310 | 230 | 54   | 610  | 760   | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 420 | 250 | 41   | 530  | 800   | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 620 | 325 | 38   | 181  | 244   | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 800 | 160 | 23   | 260  | 600   | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 1570 | 735  | 87   | 1330 | 1740  | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 2850 | 1115 | 138  | 1987 | 3675  | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 7020 | 1850 | 0.001 | 2960 | 4410  | U    | D₂  | D₂ | D₂  | D₂ | D₂  | D₂   | D₂   |
| 32930 | 2397 | 157  | 0.001 | 0.001 | U    | PD  | PD | PD  | PD | PD  | PD   | PD   |
| 1450 | 940  | 211  | 322  | 61    | U    | T₁/T₂ | D₁ | DT  | T₂ | T₂  | T₁/T₂ | T₂   |
| 3675 | 6392 | 2500 | 7691 | 5     | U    | T₁/T₂ | T₁ | T₃  | T₃ | T₃  | T₁/T₂ | T₁   |
| 100  | 200  | 110  | 670  | 11    | U    | T₃  | T₃ | T₃  | T₃ | T₂  | T₃   | T₃   |
| 150  | 22   | 9    | 60   | 11    | U    | T₃  | D₂  | T₃  | T₃ | T₃  | T₃   | T₃   |
| 860  | 1670 | 30   | 2050 | 40    | U    | T₃  | T₃ | T₃  | T₃ | T₃  | T₃   | T₃   |
| 1860 | 4980 | 0.001 | 10700 | 1600 | U    | T₃  | ND  | T₃  | T₃ | T₃  | T₃   | T₃   |
| 8   | 0.001 | 3    | 26   | 482   | S    | D₁  | ND  | D₂  | D₂ | D₁  | /     | D₁   |
| 35  | 6    | 3    | 26   | 482   | S    | D₁  | D₁  | D₁  | D₁ | D₁  | /     | D₁   |
| 6870 | 1028 | 79   | 900  | 5500  | S    | D₁  | D₁  | D₁  | D₁ | D₁  | /     | D₁   |
| 10092 | 5399 | 530  | 6500 | 37565 | S    | D₁  | D₁  | D₁  | D₁ | D₁  | /     | D₁   |
| 210  | 43   | 12   | 102  | 187   | S    | D₂  | D₂  | D₂  | D₂ | D₂  | /     | D₂   |
| 1084 | 188  | 8    | 166  | 769   | S    | D₂  | D₂  | D₂  | D₂ | D₂  | /     | D₂   |
| 1100 | 1600 | 221  | 2010 | 26    | S    | T₃  | T₃  | T₃  | T₃ | T₃  | /     | T₃   |
| 650  | 81   | 170  | 51   | 270   | D₁  | ND  | D₁  | D₁  | D₁ | D₁  | /     | D₁   |

ND, no detection; NF, no fault; Prop., proposed.